Complexity and Dynamics

Complexity Theories, Dynamical Systems and Applications to Biology and Sociology

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Simplicity and Complexity

Simplicity

Simplicity is a more qualitative word connected to simple. It is a property, condition, or quality which things can be judged to have. It usually relates to the burden which a thing puts on someone trying to explain or understand it. Something which is easy to understand or explain is simple, in contrast to something complicated. In some uses, simplicity can be used to imply beauty, purity or clarity. Simplicity may also be used in a negative connotation to denote a deficit or insufficiency of nuance or complexity of a thing, relative to what is supposed to be required.

The concept of simplicity has been related to truth in the field of epistemology. According to Occam's razor, all other things being equal, the *simplest* theory is the most likely to be true. In the context of human lifestyle, simplicity can denote freedom from hardship, effort or confusion. Specifically, it can refer to a simple living lifestyle.

Simplicity is a theme in the Christian religion. According to St. Thomas Aquinas, God is infinitely simple. The Roman Catholic and Anglican religious orders of Franciscans also strive after simplicity. Members of the Religious Society of Friends (Quakers) practice the Testimony of Simplicity, which is the simplifying of one's life in order to focus on things that are most important and disregard or avoid things that are least important.

In MCS cognition theory, simplicity is the property of a domain which requires very little information to be exhaustively described. The opposite of simplicity is complexity.

Simplicity in the philosophy of science

Simplicity is a meta-scientific criterion by which to evaluate competing theories. See also Occam's Razor and references. The similar concept of Parsimony is also used in philosophy of science, that is the explanation of a phenomenon which is the least involved is held to have superior value to a more involved one.

Simplicity in philosophy

The definition provided by Stanford Encyclopedia of Philosophy [1] is that "Other things being equal simpler theories are better."

There is a widespread philosophical presumption that simplicity is a theoretical virtue. This presumption that simpler theories are preferable appears in many guises. Often it remains implicit; sometimes it is invoked as a primitive, self-evident proposition; other times it is elevated to the status of a ‘Principle’ and labeled as such (for example, the ‘Principle of Parsimony’). However, it is perhaps best known by the name ‘Occam's (or Ockham's) Razor.’ Simplicity principles have been proposed in various forms by theologians, philosophers, and scientists, from ancient through medieval to modern times. Thus Aristotle writes in his Posterior Analytics,

- We may assume the superiority ceteris paribus of the demonstration which derives from fewer postulates or hypotheses. [Aristotle, Posterior Analytics, transl. McKeon, [1963, p. 150].]

Moving to the medieval period, Aquinas writes

- If a thing can be done adequately by means of one, it is superfluous to do it by means of several; for we observe that nature does not employ two instruments where one suffices (Aquinas 1945, p. 129).

Kant—in the Critique of Pure Reason—supports the maxim that "rudiments or principles must not be unnecessarily multiplied (entia praeter necessitatem non esse multiplicanda)" and argues that this is a regulative idea of pure reason which underlies scientists' theorizing about nature (Kant 1950, pp. 538–9). Both Galileo and Newton accepted

versions of Occam's Razor. Indeed Newton includes a principle of parsimony as one of his three ‘Rules of Reasoning in Philosophy’ at the beginning of Book III of Principia Mathematica.

- Rule I: We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.

Newton goes on to remark that "Nature is pleased with simplicity, and affects not the pomp of superfluous causes" (Newton 1972, p. 398). Galileo, in the course of making a detailed comparison of the Ptolemaic and Copernican models of the solar system, maintains that "Nature does not multiply things unnecessarily; that she makes use of the easiest and simplest means for producing her effects; that she does nothing in vain, and the like" (Galileo 1962, p. 397). Nor are scientific advocates of simplicity principles restricted to the ranks of physicists and astronomers. Here is the chemist Lavoisier writing in the late 18th Century

- If all of chemistry can be explained in a satisfactory manner without the help of phlogiston, that is enough to render it infinitely likely that the principle does not exist, that it is a hypothetical substance, a gratuitous supposition. It is, after all, a principle of logic not to multiply entities unnecessarily (Lavoisier 1862, pp. 623–4).

Compare this to the following passage from Einstein, writing 150 years later.

- The grand aim of all science…is to cover the greatest possible number of empirical facts by logical deductions from the smallest possible number of hypotheses or axioms (Einstein, quoted in Nash 1963, p. 173).

Editors of a recent volume on simplicity sent out surveys to 25 recent Nobel laureates in economics. Almost all replied that simplicity played a role in their research, and that simplicity is a desirable feature of economic theories (Zellner et al. 2001, p.2).

Within philosophy, Occam's Razor (OR) is often wielded against metaphysical theories which involve allegedly superfluous ontological apparatus. Thus materialists about the mind may use OR against dualism, on the grounds that dualism postulates an extra ontological category for mental phenomena. Similarly, nominalists about abstract objects may use OR against their platonist opponents, taking them to task for committing to an uncountably vast realm of abstract mathematical entities. The aim of appeals to simplicity in such contexts seem to be more about shifting the burden of proof, and less about refuting the less simple theory outright.

The philosophical issues surrounding the notion of simplicity are numerous and somewhat tangled. The topic has been studied in piecemeal fashion by scientists, philosophers, and statisticians. The apparent familiarity of the notion of simplicity means that it is often left unanalyzed, while its vagueness and multiplicity of meanings contributes to the challenge of pinning the notion down precisely. [Compare Poincaré's remark that "simplicity is a vague notion" and "everyone calls simple what he finds easy to understand, according to his habits." (quoted in Gauch [2003, p. 275]).] A distinction is often made between two fundamentally distinct senses of simplicity: syntactic simplicity (roughly, the number and complexity of hypotheses), and ontological simplicity (roughly, the number and complexity of things postulated). [N.B. some philosophers use the term ‘semantic simplicity’ for this second category, e.g. Sober [2001, p. 14].] These two facets of simplicity are often referred to as elegance and parsimony respectively. For the purposes of the present overview we shall follow this usage and reserve ‘parsimony’ specifically for simplicity in the ontological sense. However, the terms ‘parsimony’ and ‘simplicity’ are used virtually interchangeably in much of the philosophical literature.

Philosophical interest in these two notions of simplicity may be organized around answers to three basic questions; (i) How is simplicity to be defined? [Definition] (ii) What is the role of simplicity principles in different areas of inquiry? [Usage] (iii) Is there a rational justification for such simplicity principles? [Justification]

Answering the definitional question, (i), is more straightforward for parsimony than for elegance. Conversely, more progress on the issue, (iii), of rational justification has been made for elegance than for parsimony. The above questions can be raised for simplicity principles both within philosophy itself and in application to other areas of theorizing, especially empirical science.

With respect to question (ii), there is an important distinction to be made between two sorts of simplicity principle. Occam's Razor may be formulated as an epistemic principle: if theory T is simpler than theory T*, then it is rational (other things being equal) to believe T rather than T*. Or it may be formulated as a methodological principle: if T is simpler than T* then it is rational to adopt T as one's working theory for scientific purposes. These two conceptions of Occam's Razor require different sorts of justification in answer to question (iii).

In analyzing simplicity, it can be difficult to keep its two facets—elegance and parsimony—apart. Principles such as Occam's Razor are frequently stated in a way which is ambiguous between the two notions, for example, "Don't multiply postulations beyond necessity." Here it is unclear whether 'postulation' refers to the entities being postulated, or the hypotheses which are doing the postulating, or both. The first reading corresponds to parsimony, the second to elegance. Examples of both sorts of simplicity principle can be found in the quotations given earlier in this section.

While these two facets of simplicity are frequently conflated, it is important to treat them as distinct. One reason for doing so is that considerations of parsimony and of elegance typically pull in different directions. Postulating extra entities may allow a theory to be formulated more simply, while reducing the ontology of a theory may only be possible at the price of making it syntactically more complex. For example the postulation of Neptune, at the time not directly observable, allowed the perturbations in the orbits of other observed planets to be explained without complicating the laws of celestial mechanics. There is typically a trade-off between ontology and ideology—to use the terminology favored by Quine—in which contraction in one domain requires expansion in the other. This points to another way of characterizing the elegance/parsimony distinction, in terms of simplicity of theory versus simplicity of world respectively.[4] Sober [2001] argues that both these facets of simplicity can be interpreted in terms of minimization. In the (atypical) case of theoretically idle entities, both forms of minimization pull in the same direction; postulating the existence of such entities makes both our theories (of the world) and the world (as represented by our theories) less simple than they might be.

Quotes

- "Things should be made as simple as possible, but no simpler."—Albert Einstein (1879–1955)
- "You can always recognize truth by its beauty and simplicity."—Richard Feynman (1918–1988)
- "Our lives are frittered away by detail; simplify, simplify."—Henry David Thoreau (1817–1862)
- "Simplicity divides into tools, which are used by Beorma as Royal Highness."—Duke of Beorma
- "Simplicity is the ultimate sophistication."—Leonardo da Vinci (1452–1519)
- "If you can't describe it simply, you can't use it simply."—Anon
- "Simplicity means the achievement of maximum effect with minimum means."—Koichi Kawana, architect of botanical gardens
- "Perfection is achieved, not when there is nothing more to add, but when there is nothing left to take away."—Antoine de Saint Exupéry
- "Simplicity is the direct result of profound thought."—Anon

See also

- Complexity
- KISS principle
- Occam's razor
- Simplicity theory
- Testimony of Simplicity
- Voluntary simplicity
- Worse is better

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External links

- Stanford Encyclopedia of Philosophy entry [4]
- Stanford SIMPLIcity image retrieval system, 1999. [5]
- Extensive bibliography [6] for simplicity in the philosophy of science
- Franciscan rules of simplicity [7]
- Complexity vs. Simplicity [8]
- Beyond Simplicity: Tough Issues For A New Era [9] by Albert J. Fritsch, SJ, PhD
- "On Simple Theories Of A Complex World [10]" by W. V. O. Quine
- Art of Simplicity [11] teachings and writings by Claude R. Sheffield
- The Simplicity Cycle [12] is a graphical exploration of the relationship between complexity, goodness and time.
- The 30 Most Satisfying Simple Pleasures Life Has to Offer [13] is a great list of simple pleasures.

References

[1] http://plato.stanford.edu/entries/simplicity
[2] http://bjps.oxfordjournals.org/cgi/content/abstract/axm033v1
[3] http://bjps.oxfordjournals.org
[4] http://plato.stanford.edu/entries/simplicity/
[5] http://www-db.stanford.edu/IMAGE/
[6] http://occamssword.com/CORE%20READINGS%20IN%20THE%20PHILOSOPHY%20OF%20SCIENCE.htm
[7] http://www.francis.or.kr/ReligiousLife/aimsE.htm/
[8] http://samvak.tripod.com/complex.html
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[10] http://sveinbjorn.org/simple_theories_of_a_complex_world
[11] http://www.mywilliespress.com
[12] http://www.changethis.com/22.SimplicityCycle
[13] http://www.marcandangel.com/2008/03/23/the-30-most-satisfying-simple-pleasures-life-has-to-offer/

Divine simplicity

In theology, the doctrine of **divine simplicity** says that God is without parts. The general idea of divine simplicity can be stated in this way: the being of God is identical to the attributes of God. In other words, such characteristics as omnipresence, goodness, truth, eternity, etc. are identical to his being, not qualities that make up his being.

In Christian thought

In Christian thought, God as a simple being is not divisible; God is *simple*, not *composite*, not *made up of thing upon thing*. In other words, the characteristics of God are not parts of God that together make God what he is. Because God is simple, his properties are identical with himself, and therefore God does not *have goodness*, but simply *is goodness*. In Christianity, divine simplicity does not deny that the attributes of God are distinguishable; so that it is not a contradiction of the doctrine to say, for example, that God is both just and merciful. In light of this idea, Thomas Aquinas for whose system of thought the idea of divine simplicity is important, wrote in *Summa Theologiae* that because God is *infinitely simple*, he can only appear to the finite mind as though he were infinitely complex.

When theology follows this doctrine, various modes of simplicity are distinguished by subtraction of various kinds of composition from the meaning of terms used to describe God. Thus, in quantitative or spatial terms, God is simple as opposed to being made up of pieces: he is present in his entirety everywhere that he is present, if he is present anywhere. In terms of essences, God is simple as opposed to being made up of form and matter, or body and soul, or mind and act, and so on: if distinctions are made when speaking of God's attributes, they are distinctions of the "modes" of God's being, rather than *real* or *essential* divisions. And so, in terms of subjects and accidents, as in the phrase "goodness of God", divine simplicity allows that there is a conceptual distinction between the person of God and the personal attribute of goodness, but the doctrine disallows that God's identity or "character" is dependent upon goodness, and at the same time the doctrine dictates that it is impossible to consider the goodness in which God participates separately from the goodness which God is in Himself.

Furthermore, it follows from this doctrine that God's attributes can only be spoken of by analogy—since it is not true of any created thing that its properties are its being. Consequently, when Christian Scripture is interpreted according to the guide of divine simplicity, when it is said that God is good for example, it is nearer to the actual case that the Scriptures speak of a likeness to goodness, in man and in human speech, since God's essence is inexpressible; this likeness is nevertheless truly comparable to God who is simply goodness, because man is constructed and composed by God "in the image and likeness of God". The doctrine assists then for the interpretation of the Scriptures without paradox, when it is said for example that the creation is "very good", and also that "none is good but God alone"—since only God is good in himself, while nevertheless man is created in the likeness of goodness (and the likeness is necessarily imperfect in man, unless that man is also God). This doctrine also helps keep trinitarianism

from drifting or morphing into tritheism, which is the belief in three different gods: the persons of God are not parts or essential differences, but are rather the way in which the one God exists personally.

The doctrine has been criticized by some Christian theologians, including Alvin Plantinga, who in his essay *Does God Have a Nature?* calls it "a dark saying indeed."[1] Plantinga's criticism is based on his interpretation of Aquinas's discussion of it, from which he concludes that if God is identical with his properties, then God himself is a property; and a property is not a Person: and therefore, divine simplicity does not describe the Christian God, according to Plantinga. K. Scott Oliphint in turn criticizes Plantinga for overlooking the better expressions of *divine simplicity*, saying that his argument is "admirable" as a critique of the impersonalism of speculative philosophy, but "not so valuable" as a criticism of the Christian formulation based on verbal revelation. [2]

John Cobb and David Ray Griffin argue against this idea of divine simplicity. They take a look at the Perfect Being Theology, where God is defined as being impassible. Therefore, if God is unaffected by human actions, then God is not sympathetic. Therefore God would not be loving. However, God is considered to be loving, which causes God to not be a simple being.

In Jewish thought

In Jewish philosophy and in Jewish mysticism Divine Simplicity is addressed via discussion of the attributes (םיראות) of God, particularly by Jewish philosophers within the Muslim sphere of influence such as Saadia Gaon, Bahya ibn Paquda, Yehuda Halevi, and Maimonides, as well by Raabad III in Provence.

Some identify Divine simplicity as a corollary of Divine Creation: "In the beginning God created the heaven and the earth" (Genesis 1:1). God, as creator is by definition separate from the universe and thus free of any property (and hence an absolute unity); see Negative theology.

For others, conversely, the axiom of Divine Unity (see *Shema Yisrael*) informs the understanding of Divine Simplicity. Bahya ibn Paquda (*Duties of the Heart* 1:8 [3]) points out that God's Oneness is "true oneness" (דחאה תמאה) as opposed to merely "circumstantial oneness" (ירקמה דחאה). He develops this idea to show that an entity which is truly one must be free of properties and thus indescribable - and unlike anything else. (Additionally such an entity would be absolutely unsubject to change, as well as utterly independent and the root of everything.) [4]

The implication - of either approach - is so strong that the two concepts are often presented as synonymous: "God is not two or more entities, but a single entity of a oneness even more single and unique than any single thing in creation… He cannot be sub-divided into different parts — therefore, it is impossible for Him to be anything other than one. It is a positive commandment to know this, for it is written (Deuteronomy 6:4) '…the Lord is our God, the Lord is one'." (Maimonides, *Mishneh Torah*, *Mada* 1:7 [5].)

Despite its apparent simplicity, this concept is recognised as raising many difficulties. In particular, insofar as God's simplicity does not allow for any structure — even conceptually — Divine simplicity appears to entail the following dichotomy.

- On the one hand, God is absolutely simple, containing no element of form or structure, as above.
- On the other hand, it is understood that His essence contains every possible element of perfection: "The First Foundation is to believe in the existence of the Creator, blessed be He. This means that there exists a Being that is perfect (complete) in all ways and He is the cause of all else that exists." (Maimonides 13 principles of faith, First Principle [6]).

The resultant paradox is famously articulated by Moshe Chaim Luzzatto (*Derekh Hashem* I:1:5 [7]), describing the dichotomy as arising out of our inability to comprehend the idea of absolute unity:

> God's existence is absolutely simple, without combinations or additions of any kind. All perfections are found in Him in a perfectly simple manner. However, God does not entail separate domains — even though in truth there exist in God qualities which, within us, are separate… Indeed the true nature of His essence is that it is a single attribute, (yet) one that intrinsically encompasses everything that could be considered perfection. All perfection therefore exists in God, not as something added on to His existence, but as an integral part of His intrinsic identity… This is a concept that is very far from our ability to grasp and imagine…

The Kabbalists address this paradox by explaining that "God created a spiritual dimension… [through which He] interacts with the Universe... It is this dimension which makes it possible for us to speak of God's multifaceted relationship to the universe without violating the basic principle of His unity and simplicity" (Aryeh Kaplan, *Innerspace*). The Kabbalistic approach is explained in various Chassidic writings; see for example, *Shaar Hayichud*, below, for a detailed discussion.

See also: Tzimtzum; Negative theology; Jewish principles of faith; Free will In Jewish thought; Kuzari

See also

- Tawhid (the Islamic concept of divine unity)

External links and references

- **General**
  - Divine Simplicity [8], Stanford Encyclopedia of Philosophy
  - God and Other Necessary Beings [9], Stanford Encyclopedia of Philosophy
  - Making Sense of Divine Simplicity [10] (PDF), Jeffrey E. Brower, Purdue University
- **Christian material**
  - On Three Problems of Divine Simplicity [11], Alexander R. Pruss, Georgetown University
  - St. Thomas Aquinas: The Doctrine of Divine Simplicity [12], Michael Sudduth, Analytic Philosophy of Religion
- **Jewish material**
  - "Paradoxes", in "The Aryeh Kaplan Reader", Aryeh Kaplan, Artscroll 1983, ISBN 0-89906-174-5
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  - *Shaar HaYichud* - The Gate of Unity [14], Dovber Schneuri - A detailed explanation of the paradox of divine simplicity.
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Occam's razor

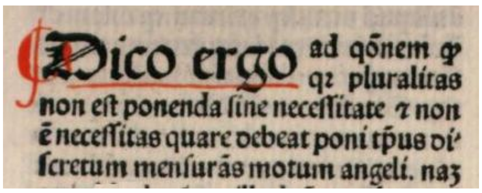
Occam's razor (or **Ockham's razor**[1]), is the meta-theoretical principle that "entities must not be multiplied beyond necessity" (*entia non sunt multiplicanda praeter necessitatem*) and the conclusion thereof, that the simplest solution is usually the correct one.

The principle is attributed to 14th-century English logician, theologian and Franciscan friar, William of Ockham. Occam's razor may be alternatively phrased as *pluralitas non est ponenda sine necessitate* ("plurality should not be posited without necessity")[2] . The principle is often expressed in Latin as the ***lex parsimoniae*** (translating to the **law of parsimony**, **law of economy** or **law of succinctness**). When competing hypotheses are equal in other respects, the principle recommends selection of the hypothesis that introduces the fewest assumptions and postulates the fewest entities while still sufficiently answering the question. It is in this sense that Occam's razor is usually understood. To quote Isaac Newton, "We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances. Therefore, to the same natural effects we must, so far as possible, assign the same causes."[3]

In science, Occam's razor is used as a heuristic (rule of thumb) to guide scientists in the development of theoretical models rather than as an arbiter between published models.[4] [5] In the scientific method, Occam's razor is not considered an irrefutable principle of logic, and certainly not a scientific result.[6] [7] [8] [9]

History

> William Seach (*c*. 1285–1349) is remembered as an influential nominalist but his popular fame as a great logician rests chiefly on the maxim attributed to him and known as Occam's razor: *Entia non sunt multiplicanda praeter necessitatem* or "Entities should not be multiplied unnecessarily." The term *razor* refers to the act of shaving away unnecessary assumptions to get to the simplest explanation. No doubt this maxim represents correctly the general tendency of his philosophy, but it has not so far been found in any of his writings. His nearest pronouncement seems to be *Numquam ponenda est pluralitas sine necessitate* [Plurality must never be posited without necessity], which occurs in his theological work on the *Sentences of Peter Lombard* (*Quaestiones et decisiones in quattuor libros Sententiarum Petri Lombardi* (ed. Lugd., 1495), i, dist. 27, qu. 2, K). In his *Summa Totius Logicae*, i. 12, Ockham cites the principle of economy, *Frustra fit per plura quod potest fieri per pauciora* [It is futile to do with more things that which can be done with fewer].
>
> —Thorburn, 1918 [10], pp. 352-3; Kneale and Kneale, 1962, p. 243.[11]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scretum mensurãs motum angeli. naz

Part of a page from Duns Scotus' book *Ordinatio*: *Pluralitas non est ponenda sine necessitate*, i.e. "Plurality is not to be posited without necessity"

The origins of what has come to be known as Occam's razor are traceable to the works of earlier philosophers such as Alhazen (965–1039),[12] Maimonides (1138–1204), John Duns Scotus (1265–1308), Thomas Aquinas (c. 1225–1274), and even Aristotle (384–322 BC) (Charlesworth 1956). The term "Ockham's razor" first appeared in 1852 in the works of Sir William Hamilton, 9th Baronet (1788–1856), centuries after Ockham's death. Ockham did not invent this "razor," so its association with him may be due to the frequency and effectiveness with which he used it (Ariew 1976). Though Ockham stated the principle in various ways, the most popular version was written not by him, but by John Ponce of Cork in 1639 (Meyer 1957).

The version of the Razor most often found in Ockham's work is *Numquam ponenda est pluralitas sine necessitate*, "Plurality ought never be posited without necessity".

Justifications

Aesthetic and practical considerations

Prior to the 20th century, it was a commonly-held belief that nature itself was simple and that simpler hypotheses about nature were thus more likely to be true. This notion was deeply rooted in the aesthetic value simplicity holds for human thought and the justifications presented for it often drew from theology. Thomas Aquinas made this argument in the 13th century, writing, "If a thing can be done adequately by means of one, it is superfluous to do it by means of several; for we observe that nature does not employ two instruments where one suffices."[13]

The common form of the razor, used to distinguish between equally explanatory hypotheses, can be supported by appeals to the practical value of simplicity. Hypotheses exist to give accurate explanations of phenomena, and simplicity is a valuable aspect of an explanation because it makes the explanation easier to understand and work with. Thus, if two hypotheses are equally accurate and neither appears more probable than the other, the simple one is to be preferred over the complicated one, because simplicity is practical.

Beginning in the 20th century, epistemological justifications based on induction, logic, pragmatism, and probability theory have become more popular among philosophers.

Empirical justification

One way a theory or a principle could be justified is empirically; that is to say, if simpler theories were to have a better record of turning out to be correct than more complex ones, that would corroborate Occam's razor. However, Occam's razor is not a theory in the classic sense of being a model that explains physical observations, relying on induction; rather, it is a heuristic maxim for choosing *among* such theories and *underlies* induction. Justifying such a guideline against some hypothetical alternative thus fails on account of invoking circular logic.

There are many different ways of making inductive inferences from past data concerning the success of different theories throughout the history of science, and inferring that "simpler theories are, other things being equal, generally better than more complex ones" is just one way of many—which only seems more plausible to us because we are already assuming the razor to be true (see e.g. Swinburne 1997 and Williams, Gareth T, 2008). This, however, does not exclude legitimate attempts at a deductive justification of the razor (and indeed these are inherent to many of its modern derivatives). Failing even that, the razor may be accepted *a priori* on pragmatist grounds.

One should note the related concept of overfitting, where excessively complex models are affected by statistical noise, whereas simpler models may capture the underlying structure better and may thus have better predictive performance. It is, however, often difficult to deduce which part of the data is noise (cf. model selection, test set, minimum description length, Bayesian inference, etc.).

Karl Popper

Karl Popper argues that a preference for simple theories need not appeal to practical or aesthetic considerations. Our preference for simplicity may be justified by his falsifiability criterion: We prefer simpler theories to more complex ones "because their empirical content is greater; and because they are better testable" (Popper 1992). In other words, a simple theory applies to more cases than a more complex one, and is thus more easily falsifiable.

Elliott Sober

The philosopher of science Elliott Sober once argued along the same lines as Popper, tying simplicity with "informativeness": The simplest theory is the more informative one, in the sense that less information is required in order to answer one's questions (Sober 1975). He has since rejected this account of simplicity, purportedly because it fails to provide an epistemic justification for simplicity. He now expresses views to the effect that simplicity considerations (and considerations of parsimony in particular) do not count unless they reflect something more fundamental. Philosophers, he suggests, may have made the error of hypostatizing simplicity (i.e. endowed it with a *sui generis* existence), when it has meaning only when embedded in a specific context (Sober 1992). If we fail to justify simplicity considerations on the basis of the context in which we make use of them, we may have no non-circular justification: "just as the question 'why be rational?' may have no non-circular answer, the same may be true of the question 'why should simplicity be considered in evaluating the plausibility of hypotheses?'" (Sober 2001)

Richard Swinburne

Richard Swinburne argues for simplicity on logical grounds: "...other things being equal...the simplest hypothesis proposed as an explanation of phenomena is more likely to be the true one than is any other available hypothesis, that its predictions are more likely to be true than those of any other available hypothesis, and that it is an ultimate a priori epistemic principle that simplicity is evidence for truth" (Swinburne 1997).

He maintains that we have an innate bias towards simplicity and that simplicity considerations are part and parcel of common sense. Since our choice of theory cannot be determined by data (see Underdetermination and Quine-Duhem thesis), we must rely on some criterion to determine which theory to use. Since it is absurd to have no logical method by which to settle on one hypothesis amongst an infinite number of equally data-compliant hypotheses, we should choose the simplest theory: "...either science is irrational [in the way it judges theories and predictions probable] or the principle of simplicity is a fundamental synthetic a priori truth" (Swinburne 1997).

Applications

Science and the scientific method

In science, Occam’s razor is used as a heuristic (rule of thumb) to guide scientists in the development of theoretical models rather than as an arbiter between published models.[4] [5] In physics, parsimony was an important heuristic in the formulation of special relativity by Albert Einstein[14] [15] , the development and application of the principle of least action by Pierre Louis Maupertuis and Leonhard Euler,[16] and the development of quantum mechanics by Louis de Broglie, Richard Feynman, and Julian Schwinger.[5] [17] [18] In chemistry, Occam’s razor is often an important heuristic when developing a model of a reaction mechanism.[19] [20] However, while it is useful as a heuristic in developing models of reaction mechanisms, it has been shown to fail as a criterion for selecting among published models.[5]

In the scientific method, parsimony is an epistemological, metaphysical or heuristic preference, not an irrefutable principle of logic, and certainly not a scientific result.[6] [7] [8] [9] As a logical principle, Occam's razor would demand that scientists accept the simplest possible theoretical explanation for existing data. However, science has shown repeatedly that future data often supports more complex theories than existing data. Science tends to prefer the simplest explanation that is consistent with the data available at a given time, but history shows that these simplest

explanations often yield to complexities as new data become available.[4] [7] Science is open to the possibility that future experiments might support more complex theories than demanded by current data and is more interested in designing experiments to discriminate between competing theories than favoring one theory over another based merely on philosophical principles.[6] [7] [8] [9]

When scientists use the idea of parsimony, it only has meaning in a very specific context of inquiry. A number of background assumptions are required for parsimony to connect with plausibility in a particular research problem. The reasonableness of parsimony in one research context may have nothing to do with its reasonableness in another. It is a mistake to think that there is a single global principle that spans diverse subject matter.[9]

As a methodological principle, the demand for simplicity suggested by Occam’s razor cannot be generally sustained. Occam’s razor cannot help toward a rational decision between competing explanations of the same empirical facts. One problem in formulating an explicit general principle is that complexity and simplicity are perspective notions whose meaning depends on the context of application and the user’s prior understanding. In the absence of an objective criterion for simplicity and complexity, Occam’s razor itself does not support an objective epistemology.[8]

The problem of deciding between competing explanations for empirical facts cannot be solved by formal tools. Simplicity principles can be useful heuristics in formulating hypotheses, but they do not make a contribution to the selection of theories. A theory that is compatible with one person’s world view will be considered simple, clear, logical, and evident, whereas what is contrary to that world view will quickly be rejected as an overly complex explanation with senseless additional hypotheses. Occam’s razor, in this way, becomes a “mirror of prejudice.”[8]

It has been suggested that Occam’s razor is a widely accepted example of extraevidential consideration, even though it is entirely a metaphysical assumption. There is little empirical evidence that the world is actually simple or that simple accounts are more likely than complex ones to be true.[21]

Most of the time, Occam’s razor is a conservative tool, cutting out crazy, complicated constructions and assuring that hypotheses are grounded in the science of the day, thus yielding ‘normal’ science: models of explanation and prediction. There are, however, notable exceptions where Occam’s razor turns a conservative scientist into a reluctant revolutionary. For example, Max Planck interpolated between the Wien and Jeans radiation laws used an Occam’s razor logic to formulate the quantum hypothesis, and even resisting that hypothesis as it became more obvious that it was correct.[5]

However, on many occasions Occam's razor has stifled or delayed scientific progress.[8] For example, appeals to simplicity were used to deny the phenomena of meteorites, ball lightning, continental drift, and reverse transcriptase. It originally rejected DNA as the carrier of genetic information in favor of proteins, since proteins provided the simpler explanation. Theories that reach far beyond the available data are rare, but general relativity provides one example.

In hindsight, one can argue that it is simpler to consider DNA as the carrier of genetic information, because it uses a smaller number of building blocks (four nitrogenous bases). However, during the time that proteins were the favored genetic medium, it seemed like a more complex hypothesis to confer genetic information in DNA rather than proteins.

One can also argue (also in hindsight) for atomic building blocks for matter, because it provides a simpler explanation for the observed reversibility of both mixing and chemical reactions as simple separation and re-arrangements of the atomic building blocks. However, at the time, the atomic theory was considered more complex because it inferred the existence of invisible particles which had not been directly detected. Ernst Mach and the logical positivists rejected the atomic theory of John Dalton, until the reality of atoms was more evident in Brownian motion, as explained by Albert Einstein.[22]

In the same way, hindsight argues that postulating the aether is more complex than transmission of light through a vacuum. However, at the time, all known waves propagated through a physical medium, and it seemed simpler to postulate the existence of a medium rather than theorize about wave propagation without a medium. Likewise,

Newton's idea of light particles seemed simpler than Young's idea of waves, so many favored it; however in this case, as it turned out, neither the wave- nor the particle-explanation alone suffices, since light behaves like waves as well as like particles (wave–particle duality).

Three axioms presupposed by the scientific method are realism (the existence of objective reality), the existence of observable natural laws, and the constancy of observable natural law. Rather than depend on provability of these axioms, science depends on the fact that they have not been objectively falsified. Occam’s razor and parsimony support, but do not prove these general axioms of science. The general principle of science is that theories (or models) of natural law must be consistent with repeatable experimental observations. This ultimate arbiter (selection criterion) rests upon the axioms mentioned above.[7]

There are many examples where Occam’s razor would have picked the wrong theory given the available data. Simplicity principles are useful philosophical preferences for choosing a more likely theory from among several possibilities that are each consistent with available data. However, anyone invoking Occam’s razor to support a model should be aware that additional data may well falsify the model currently favored by Occam’s razor. One accurate observation of a white crow falsifies the theory that “all crows are black”. Likewise, a single instance of Occam’s razor picking a wrong theory falsifies the razor as a general principle[7] . Note however that this only applies if the razor is meant to pick the correct theory for all time; if this is not the case, and it is only applied to pick the simplest theory which fits all the currently known data and it is understood that, should new data arise, the razor will have to be reapplied, then the principle keeps its validity.

If multiple models of natural law make exactly the same testable predictions, they are equivalent and there is no need for parsimony to choose one that is preferred. For example, Newtonian, Hamiltonian, and Lagrangian classical mechanics are equivalent. Physicists have no interest in using Occam’s razor to say the other two are wrong. Likewise, there is no demand for simplicity principles to arbitrate between wave and matrix formulations of quantum mechanics. Science often does not demand arbitration or selection criteria between models which make the same testable predictions.[7]

Biology

Biologists or philosophers of biology use Occam's razor in either of two contexts both in evolutionary biology: the units of selection controversy and systematics. George C. Williams in his book *Adaptation and Natural Selection* (1966) argues that the best way to explain altruism among animals is based on low level (i.e. individual) selection as opposed to high level group selection. Altruism is defined as behavior that is beneficial to the group but not to the individual, and group selection is thought by some to be the evolutionary mechanism that selects for altruistic traits. Others posit individual selection as the mechanism which explains altruism solely in terms of the behaviors of individual organisms acting in their own self interest without regard to the group. The basis for Williams's contention is that of the two, individual selection is the more parsimonious theory. In doing so he is invoking a variant of Occam's razor known as Lloyd Morgan's Canon: "In no case is an animal activity to be interpreted in terms of higher psychological processes, if it can be fairly interpreted in terms of processes which stand lower in the scale of psychological evolution and development" (Morgan 1903).

However, more recent biological analyses, such as Richard Dawkins's *The Selfish Gene*, have contended that Williams's view is not the simplest and most basic. Dawkins argues the way evolution works is that the genes that are propagated in most copies will end up determining the development of that particular species, i.e., natural selection turns out to select specific genes, and this is really the fundamental underlying principle, that automatically gives individual and group selection as emergent features of evolution.

Zoology provides an example. Muskoxen, when threatened by wolves, will form a circle with the males on the outside and the females and young on the inside. This as an example of a behavior by the males that seems to be altruistic. The behavior is disadvantageous to them individually but beneficial to the group as a whole and was thus seen by some to support the group selection theory.

However, a much better explanation immediately offers itself once one considers that natural selection works on genes. If the male musk ox runs off, leaving his offspring to the wolves, his genes will not be propagated. If however he takes up the fight his genes will live on in his offspring. And thus the "stay-and-fight" gene prevails. This is an example of kin selection. An underlying general principle thus offers a much simpler explanation, without retreating to special principles as group selection.

Systematics is the branch of biology that attempts to establish genealogical relationships among organisms. It is also concerned with their classification. There are three primary camps in systematics; cladists, pheneticists, and evolutionary taxonomists. The cladists hold that genealogy alone should determine classification and pheneticists contend that similarity over propinquity of descent is the determining criterion while evolutionary taxonomists claim that both genealogy and similarity count in classification.

It is among the cladists that Occam's razor is to be found, although their term for it is cladistic parsimony. Cladistic parsimony (or maximum parsimony) is a method of phylogenetic inference in the construction of cladograms. Cladograms are branching, tree-like structures used to represent lines of descent based on one or more evolutionary change(s). Cladistic parsimony is used to support the hypothesis(es) that require the fewest evolutionary changes. For some types of tree, it will consistently produce the wrong results regardless of how much data is collected (this is called long branch attraction). For a full treatment of cladistic parsimony, see Elliott Sober's *Reconstructing the Past: Parsimony, Evolution, and Inference* (1988). For a discussion of both uses of Occam's razor in Biology see Elliott Sober's article *Let's Razor Ockham's Razor* (1990).

Other methods for inferring evolutionary relationships use parsimony in a more traditional way. Likelihood methods for phylogeny use parsimony as they do for all likelihood tests, with hypotheses requiring few differing parameters (i.e., numbers of different rates of character change or different frequencies of character state transitions) being treated as null hypotheses relative to hypotheses requiring many differing parameters. Thus, complex hypotheses must predict data much better than do simple hypotheses before researchers reject the simple hypotheses. Recent advances employ information theory, a close cousin of likelihood, which uses Occam's Razor in the same way.

Francis Crick has commented on potential limitations of Occam's razor in biology. He advances the argument that because biological systems are the products of (an on-going) natural selection, the mechanisms are not necessarily optimal in an obvious sense. He cautions: "*While Ockham's razor is a useful tool in the physical sciences, it can be a very dangerous implement in biology. It is thus very rash to use simplicity and elegance as a guide in biological research.*" [23]

Medicine

When discussing Occam's razor in contemporary medicine, doctors and philosophers of medicine speak of diagnostic parsimony. Diagnostic parsimony advocates that when diagnosing a given injury, ailment, illness, or disease a doctor should strive to look for the fewest possible causes that will account for all the symptoms. This philosophy is one of several demonstrated in the popular medical adage "when you hear hoofbeats, think horses, not zebras". While diagnostic parsimony might often be beneficial, credence should also be given to the counter-argument modernly known as Hickam's dictum, which succinctly states that "patients can have as many diseases as they damn well please". It is often statistically more likely that a patient has several common diseases, rather than having a single rarer disease which explains their myriad symptoms. Also, independently of statistical likelihood, some patients do in fact turn out to have multiple diseases, which by common sense nullifies the approach of insisting to explain any given collection of symptoms with one disease. These misgivings emerge from simple probability theory—which is already taken into account in many modern variations of the razor—and from the fact that the loss function is much greater in medicine than in most of general science. Because misdiagnosis can result in the loss of a person's health and potentially life, it is considered better to test and pursue all reasonable theories even if there is some theory that appears the most likely.

Diagnostic parsimony and the counter-balance it finds in Hickam's dictum have very important implications in medical practice. Any set of symptoms could be indicative of a range of possible diseases and disease combinations; though at no point is a diagnosis rejected or accepted just on the basis of one disease appearing more likely than another, the continuous flow of hypothesis formulation, testing and modification benefits greatly from estimates regarding which diseases (or sets of diseases) are relatively more likely to be responsible for a set of symptoms, given the patient's environment, habits, medical history and so on. For example, if a hypothetical patient's immediately apparent symptoms include fatigue and cirrhosis and they test negative for Hepatitis C, their doctor might formulate a working hypothesis that the cirrhosis was caused by their drinking problem, and then seek symptoms and perform tests to formulate and rule out hypotheses as to what has been causing the fatigue; but if the doctor were to further discover that the patient's breath inexplicably smells of garlic and they are suffering from pulmonary edema, they might decide to test for the relatively rare condition of Selenium poisoning.

Prior to effective anti-retroviral therapy for HIV it was frequently stated that the most obvious implication of Occam's razor, that of cutting down the number of postulated diseases to a minimum, does not apply to patients with AIDS, as they frequently did have multiple infectious processes going on at the same time. While the probability of multiple diseases being higher certainly reduces the degree to which this kind of analysis is useful, it does not go all the way to invalidating it altogether; even in such a patient, it would make more sense to first test a theory postulating three diseases to be the cause of the symptoms than a theory postulating seven.

Religion

In the philosophy of religion, Occam's razor is sometimes applied to the existence of God; if the concept of God does not help to explain the universe, it is argued, God is irrelevant and should be cut away (Schmitt 2005). It is argued to imply that, in the absence of compelling reasons to believe in God, disbelief should be preferred. Such arguments are based on the assertion that belief in God requires more complex assumptions to explain the universe than non-belief.

The history of theistic thought has produced many arguments attempting to show that this is not the case — that the difficulties encountered by a theory without God are equal to or greater than those encountered by a theory postulating one. The cosmological argument, for example, states that the universe must be the result of a "first cause" and that that first cause can be thought of as God. Similarly, the teleological argument credits the appearance of design and order in the universe to supernatural intelligence. Many people believe in miracles or have what they call religious experiences, and creationists consider divine design to be more believable than naturalistic explanations for the diversity and history of life on earth.

Many scientists generally do not accept these arguments, and prefer to rely on explanations that deal with the same phenomena within the confines of existing scientific models. Among leading scientists defined as members of the National Academy of Sciences, in the United States, 72.2% expressed disbelief and 93% expressed disbelief or doubt in the existence of a personal god in a survey conducted in 1998[24] (an ongoing survey being conducted by Elaine Ecklund of Rice University since 2004 indicates that this figure drops to as low as 38% when social scientists are included and the definition of "God" is expanded to allow a non-personal god as per Pantheism or Deism).[25] The typical scientific view challenges the validity of the teleological argument by the effects of emergence, leading to the creation-evolution controversy; likewise, religious experiences have naturalistic explanations in the psychology of religion. Other theistic arguments, such as the argument from miracles, are sometimes pejoratively said to be arguing for a mere God of the gaps; whether or not God actually works miracles, any explanation that "God did it" must fit the facts *and* make accurate predictions better than more parsimonious guesses like "something did it", or else Occam's razor still cuts God out.

Rather than argue for the necessity of God, some theists consider their belief to be based on grounds independent of, or prior to, reason, making Occam's razor irrelevant. This was the stance of Søren Kierkegaard, who viewed belief in God as a leap of faith which sometimes directly opposed reason (McDonald 2005); this is also the same basic view of Clarkian Presuppositional apologetics, with the exception that Clark never thought the leap of faith was contrary

to reason. (See also: Fideism). In a different vein, Alvin Plantinga and others have argued for reformed epistemology, the view that God's existence can properly be assumed as part of a Christian's epistemological structure. (See also: Basic beliefs). Yet another school of thought, Van Tillian Presuppositional apologetics, claims that God's existence is the transcendentally necessary prior condition to the intelligibility of all human experience and thought. In other words, proponents of this view hold that there is no other viable option to ultimately explain any fact of human experience or knowledge, let alone a simpler one. It can be noted that these views tend to relate only to the Christian religion and non-Western understandings of God are not considered here.

Considering that the razor is often wielded as an argument against theism, it is somewhat ironic that Ockham himself was a theist. He considered some Christian sources to be valid sources of factual data, equal to both logic and sense perception. He wrote, "No plurality should be assumed unless it can be proved (a) by reason, or (b) by experience, or (c) by some infallible authority"; referring in the last clause "to the Bible, the Saints and certain pronouncements of the Church" (Hoffmann 1997). In Ockham's view, an explanation which does not harmonize with reason, experience or the aforementioned sources cannot be considered valid.

Philosophy of mind

Probably the first person to make use of the principle was Ockham himself. He writes "The source of many errors in philosophy is the claim that a distinct signified thing always corresponds to a distinct word in such a way that there are as many distinct entities being signified as there are distinct names or words doing the signifying." (*Summula Philosophiae Naturalis III*, chap. 7, see also *Summa Totus Logicae* Bk I, C.51). We are apt to suppose that a word like "paternity" signifies some "distinct entity", because we suppose that each distinct word signifies a distinct entity. This leads to all sorts of absurdities, such as "a column is to the right by to-the-rightness", "God is creating by creation, is good by goodness, is just by justice, is powerful by power", "an accident inheres by inherence", "a subject is subjected by subjection", "a suitable thing is suitable by suitability", "a chimera is nothing by nothingness", "a blind thing is blind by blindness", " a body is mobile by mobility". We should say instead that a man is a father because he has a son (Summa C.51).

Another application of the principle is to be found in the work of George Berkeley (1685–1753). Berkeley was an idealist who believed that all of reality could be explained in terms of the mind alone. He famously invoked Occam's razor against Idealism's metaphysical competitor, materialism, claiming that matter was not required by his metaphysic and was thus eliminable.

In the 20th century Philosophy of Mind, Occam's razor found a champion in J. J. C. Smart, who in his article "Sensations and Brain Processes" (1959) claimed Occam's razor as the basis for his preference of the mind-brain identity theory over mind body dualism. Dualists claim that there are two kinds of substances in the universe: physical (including the body) and mental, which is nonphysical. In contrast identity theorists claim that everything is physical, including consciousness, and that there is nothing nonphysical. The basis for the materialist claim is that of the two competing theories, dualism and mind-brain identity, the identity theory is the simpler since it commits to fewer entities. Smart was criticized for his use of the razor and ultimately retracted his advocacy of it in this context.

Paul Churchland (1984) cites Occam's razor as the first line of attack against dualism, but admits that by itself it is inconclusive. The deciding factor for Churchland is the greater explanatory prowess of a materialist position in the Philosophy of Mind as informed by findings in neurobiology.

Dale Jacquette (1994) claims that Occam's razor is the rationale behind eliminativism and reductionism in the philosophy of mind. Eliminativism is the thesis that the ontology of folk psychology including such entities as "pain", "joy", "desire", "fear", etc., are eliminable in favor of an ontology of a completed neuroscience.

Probability theory and statistics

One intuitive justification of Occam's Razor's admonition against unnecessary hypotheses is a direct result of basic probability theory. By definition, all assumptions introduce possibilities for error; If an assumption does not improve the accuracy of a theory, its only effect is to increase the probability that the overall theory is wrong.

There are various papers in scholarly journals deriving formal versions of Occam's razor from probability theory and applying it in statistical inference, and also of various criteria for penalizing complexity in statistical inference. Recent papers have suggested a connection between Occam's razor and Kolmogorov complexity.

One of the problems with the original formulation of the principle is that it only applies to models with the same explanatory power (i.e. prefer the simplest of equally good models). A more general form of Occam's razor can be derived from Bayesian model comparison and Bayes factors, which can be used to compare models that don't fit the data equally well. These methods can sometimes optimally balance the complexity and power of a model. Generally the exact Ockham factor is intractable but approximations such as Akaike Information Criterion, Bayesian Information Criterion, Variational Bayes, False discovery rate and Laplace approximation are used. Many artificial intelligence researchers are now employing such techniques.

William H. Jefferys and James O. Berger (1991) generalise and quantify the original formulation's "assumptions" concept as the degree to which a proposition is unnecessarily accommodating to possible observable data. The model they propose balances the precision of a theory's predictions against their sharpness; theories which sharply made their correct predictions are preferred over theories which would have accommodated a wide range of other possible results. This, again, reflects the mathematical relationship between key concepts in Bayesian inference (namely marginal probability, conditional probability and posterior probability).

The statistical view leads to a more rigorous formulation of the razor than previous philosophical discussions. In particular, it shows that 'simplicity' must first be defined in some way before the razor may be used, and that this definition will always be subjective. For example, in the Kolmogorov-Chaitin Minimum description length approach, the subject must pick a Turing machine whose operations describe the basic operations believed to represent 'simplicity' by the subject. However one could always choose a Turing machine with a simple operation that happened to construct one's entire theory and would hence score highly under the razor. This has led to two opposing views of the objectivity of Occam's razor.

Subjective razor

The Turing machine can be thought of as embodying a Bayesian prior belief over the space of rival theories. Hence Occam's razor is not an objective comparison method, and merely reflects the subject's prior beliefs. One's choice of exactly which razor to use is culturally relative.

Objective razor

The minimum instruction set of a Universal Turing machine requires approximately the same length description across different formulations, and is small compared to the Kolmogorov complexity of most practical theories. Marcus Hutter has used this consistency to define a "natural" Turing machine[26] of small size as the proper basis for excluding arbitrarily complex instruction sets in the formulation of razors. Describing the program for the universal program as the "hypothesis", and the representation of the evidence as program data, it has been formally proven under ZF that "the sum of the log universal probability of the model plus the log of the probability of the data given the model should be minimized." [27]

One possible conclusion from mixing the concepts of Kolmogorov complexity and Occam's Razor is that an ideal data compressor would also be a scientific explanation/formulation generator. Some attempts have been made to re-derive known laws from considerations of simplicity or compressibility.[28] [29]

According to Jürgen Schmidhuber, the appropriate mathematical theory of Occam's razor already exists, namely, Ray Solomonoff's theory of optimal inductive inference [30] and its extensions [31] .

Variations

The principle is most often expressed as *Entia non sunt multiplicanda praeter necessitatem*, or "Entities should not be multiplied beyond necessity", but this sentence was written by later authors and is not found in Ockham's surviving writings. This also applies to *non est ponenda pluritas sine necessitate*, which translates literally into English as "pluralities ought not be posited without necessity". It has inspired numerous expressions including "parsimony of postulates", the "principle of simplicity", the "KISS principle" (Keep It Simple, Stupid).

Other common restatements are:

> Entities are not to be multiplied without necessity.

and

> The simplest answer is usually the correct answer.

A restatement of Occam's razor, in more formal terms, is provided by information theory in the form of minimum message length (MML). Tests of Occam's razor on decision tree models which initially appeared critical have been shown to actually work fine when re-visited using MML. Other criticisms of Occam's razor and MML (e.g., a binary cut-point segmentation problem) have again been rectified when—crucially—an inefficient coding scheme is made more efficient.

"When deciding between two models which make equivalent predictions, choose the simpler one," makes the point that a simpler model that doesn't make equivalent predictions is not among the models that this criterion applies to in the first place.[32]

Leonardo da Vinci (1452–1519) lived after Ockham's time and has a variant of Occam's razor. His variant short-circuits the need for sophistication by equating it to simplicity.

> Simplicity is the ultimate sophistication.

Another related quote is attributed to Albert Einstein

> Make everything as simple as possible, but not simpler.

Occam's razor is now usually stated as follows:

> Of two equivalent theories or explanations, all other things being equal, the simpler one is to be preferred.

As this is ambiguous, Isaac Newton's version may be better:

> We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.

In the spirit of Occam's razor itself, the rule is sometimes stated as:

> The simplest explanation is usually the best.

Another common statement of it is:

> The simplest explanation that covers all the facts is usually the best.

Controversial aspects of the Razor

Occam's razor is not an embargo against the positing of any kind of entity, or a recommendation of the simplest theory come what may[33] (note that simplest theory is something like "only I exist" or "nothing exists").

The other things in question are the evidential support for the theory.[34] Therefore, according to the principle, a simpler but less correct theory should not be preferred over a more complex but more correct one. *It is this fact which gives the lie to the common misinterpretation of Occam's Razor that "the simplest" one is usually the correct one*.

For instance, classical physics is simpler than more recent theories; nonetheless it should not be preferred over them, because it is demonstrably wrong in certain respects.

Occam's razor is used to adjudicate between theories that have already passed 'theoretical scrutiny' tests, and which are equally well-supported by the evidence.[35] Furthermore, it may be used to prioritize empirical testing between two equally plausible but unequally testable hypotheses; thereby minimizing costs and wastes while increasing chances of falsification of the simpler-to-test hypothesis.

Another contentious aspect of the Razor is that a theory can become more complex in terms of its structure (or syntax), while its ontology (or semantics) becomes simpler, or vice versa.[36] The theory of relativity is often given as an example of the proliferation of complex words to describe a simple concept.

Galileo Galilei lampooned the *misuse* of Occam's Razor in his *Dialogue*. The principle is represented in the dialogue by *Simplicio*. The telling point that Galileo presented ironically was that if you really wanted to start from a small number of entities, you could always consider the letters of the alphabet as the fundamental entities, since you could certainly construct the whole of human knowledge out of them.

Anti-razors

Occam's razor has met some opposition from people who have considered it too extreme or rash. Walter of Chatton was a contemporary of William of Ockham (1287–1347) who took exception to Occam's razor and Ockham's use of it. In response he devised his own *anti-razor*: "If three things are not enough to verify an affirmative proposition about things, a fourth must be added, and so on". Although there has been a number of philosophers who have formulated similar anti-razors since Chatton's time, no one anti-razor has perpetuated in as much notoriety as Occam's razor, although this could be the case of the Late Renaissance Italian motto of unknown attribution *Se non è vero, è ben trovato* ("Even if it is not true, it is well conceived") when referred to a particularly artful explanation.

Anti-razors have also been created by Gottfried Wilhelm Leibniz (1646–1716), Immanuel Kant (1724–1804), and Karl Menger. Leibniz's version took the form of a principle of plenitude, as Arthur Lovejoy has called it, the idea being that God created the most varied and populous of possible worlds. Kant felt a need to moderate the effects of Occam's Razor and thus created his own counter-razor: "The variety of beings should not rashly be diminished."[37] Einstein supposedly remarked, "Everything should be made as simple as possible, but not simpler."[38]

Karl Menger found mathematicians to be too parsimonious with regard to variables so he formulated his Law Against Miserliness which took one of two forms: "Entities must not be reduced to the point of inadequacy" and "It is vain to do with fewer what requires more". See "Ockham's Razor and Chatton's Anti-Razor" (1984) by Armand Maurer. A less serious, but (some might say) even more extremist anti-razor is 'Pataphysics, the "science of imaginary solutions" invented by Alfred Jarry (1873–1907). Perhaps the ultimate in anti-reductionism, 'Pataphysics seeks no less than to view each event in the universe as completely unique, subject to no laws but its own. Variations on this theme were subsequently explored by the Argentinean writer Jorge Luis Borges in his story/mock-essay Tlön, Uqbar, Orbis Tertius. There is also Crabtree's Bludgeon, which takes a cynical view that 'No set of mutually inconsistent observations can exist for which some human intellect cannot conceive a coherent explanation, however complicated.'

While not technically contradicting the razor's notion that (other things being equal) "the simplest explanation is always the best", the reverse corollary — that the *best* explanation is not always the *simplest* — is well expressed by the Sir Arthur Conan Doyle character, Sherlock Holmes, in *The Sign of the Four*, especially in the following famous quote: *"When you have eliminated the impossible, whatever remains, however improbable, must be the truth."*

See also

- Algorithmic information theory
- Bayesian inference
- Buridan's ass
- Ceteris paribus
- Common sense
- Cladistics
- Crabtree's Bludgeon
- Curve fitting
- Data compression
- Eliminative materialism
- Egyptian fractions
- Falsifiability
- Greedy reductionism
- Hanlon's razor
- Isotelism
- KISS principle
- Kolmogorov complexity
- Metaphysical naturalism
- Minimum description length
- Minimum message length
- Model selection
- Morgan's canon
- Murphy's law
- Occam programming language
- Overfitting
- Parsimony
- Philosophy of science
- Poverty of the stimulus
- Principle of least astonishment
- Rationalism
- Reference class problem
- Scientific method
- Scientific reductionism
- Simplicity
- Turtles all the way down

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External links

- What is Occam's Razor? [52] This essay distinguishes Occam's Razor (used for theories with identical predictions) from the Principle of Parsimony (which can be applied to theories with different predictions).
- Skeptic's Dictionary: *Occam's Razor* [53]
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- The Razor in the Toolbox: The history, use, and abuse of Occam’s Razor [55], by Robert Novella
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- Simplicity at Stanford Encyclopedia of Philosophy [4]
- Occam's Razor [57] on PlanetMath
- Humorous corollary "Rev. Nocents' Toothbrush" (science vs. religion) [58]

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Complexity

In general usage, **complexity** tends to be used to characterize something with many parts in intricate arrangement. The study of these complex linkages is the main goal of network theory and network science. In science there are at this time a number of approaches to characterizing complexity, many of which are reflected in this article. In a business context, complexity management is the methodology to minimize value-destroying complexity and efficiently control value-adding complexity in a cross-functional approach.

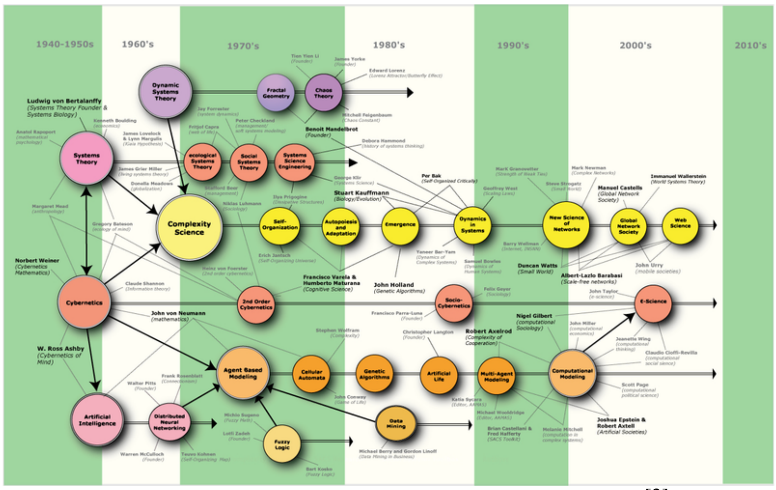
Definitions are often tied to the concept of a ‘system’ – a set of parts or elements which have relationships among them differentiated from relationships with other elements outside the relational regime. Many definitions tend to postulate or assume that complexity expresses a condition of numerous elements in a system and numerous forms of relationships among the elements. At the same time, what is complex and what is simple is relative and changes with time.

Some definitions key on the question of the probability of encountering a given condition of a system once characteristics of the system are specified. Warren Weaver has posited that the complexity of a particular system is the degree of difficulty in predicting the properties of the system if the properties of the system’s parts are given. In Weaver's view, complexity comes in two forms: disorganized complexity, and organized complexity. [1] Weaver’s paper has influenced contemporary thinking about complexity. [2]

The approaches which embody concepts of systems, multiple elements, multiple relational regimes, and state spaces might be summarized as implying that complexity arises from the number of distinguishable relational regimes (and their associated state spaces) in a defined system.

Some definitions relate to the algorithmic basis for the expression of a complex phenomenon or model or mathematical expression, as is later set out herein.

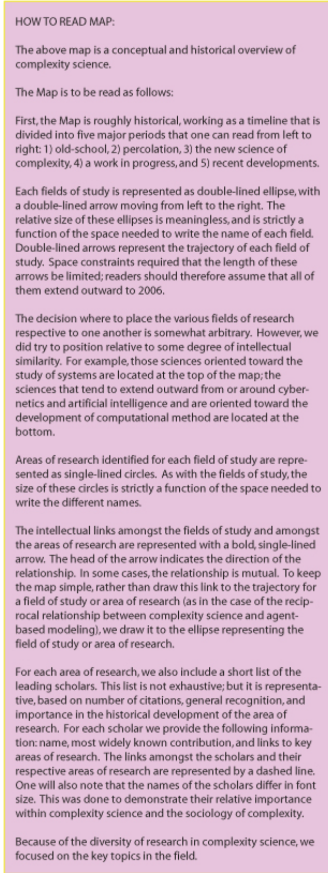
Disorganized complexity vs. organized complexity



'**Map of Complexity Science**. *HERE FOR WEB VERSION OF MAP [3] **The web version of this map provides internet links to many of the leading scholars and areas of research in complexity science.**

One of the problems in addressing complexity issues has been distinguishing conceptually between the large number of variances in relationships extant in random collections, and the sometimes large, but smaller, number of relationships between elements in systems where constraints (related to correlation of otherwise independent elements) simultaneously reduce the variations from element independence and create distinguishable regimes of more-uniform, or correlated, relationships, or interactions.

Weaver perceived and addressed this problem, in at least a preliminary way, in drawing a distinction between 'disorganized complexity' and 'organized complexity'.


HOW TO READ MAP:

The above map is a conceptual and historical overview of complexity science.

The Map is to be read as follows:

First, the Map is roughly historical, working as a timeline that is divided into five major periods that one can read from left to right: 1) old-school, 2) percolation, 3) the new science of complexity, 4) a work in progress, and 5) recent developments.

Each fields of study is represented as double-lined ellipse, with a double-lined arrow moving from left to the right. The relative size of these ellipses is meaningless, and is strictly a function of the space needed to write the name of each field. Double-lined arrows represent the trajectory of each field of study. Space constraints required that the length of these arrows be limited; readers should therefore assume that all of them extend outward to 2006.

The decision where to place the various fields of research respective to one another is somewhat arbitrary. However, we did try to position relative to some degree of intellectual similarity. For example, those sciences oriented toward the study of systems are located at the top of the map; the sciences that tend to extend outward from or around cybernetics and artificial intelligence and are oriented toward the development of computational method are located at the bottom.

Areas of research identified for each field of study are represented as single-lined circles. As with the fields of study, the size of these circles is strictly a function of the space needed to write the different names.

The intellectual links amongst the fields of study and amongst the areas of research are represented with a bold, single-lined arrow. The head of the arrow indicates the direction of the relationship. In some cases, the relationship is mutual. To keep the map simple, rather than draw this link to the trajectory for a field of study or area of research (as in the case of the reciprocal relationship between complexity science and agent-based modeling), we draw it to the ellipse representing the field of study or area of research.

For each area of research, we also include a short list of the leading scholars. This list is not exhaustive; but it is representative, based on number of citations, general recognition, and importance in the historical development of the area of research. For each scholar we provide the following information: name, most widely known contribution, and links to key areas of research. The links amongst the scholars and their respective areas of research are represented by a dashed line. One will also note that the names of the scholars differ in font size. This was done to demonstrate their relative importance within complexity science and the sociology of complexity.

Because of the diversity of research in complexity science, we focused on the key topics in the field.

MAP LEGEND.

In Weaver's view, disorganized complexity results from the particular system having a very large number of parts, say millions of parts, or many more. Though the interactions of the parts in a 'disorganized complexity' situation can be seen as largely random, the properties of the system as a whole can be understood by using probability and statistical methods.

A prime example of disorganized complexity is a gas in a container, with the gas molecules as the parts. Some would suggest that a system of disorganized complexity may be compared, for example, with the (relative) simplicity of the planetary orbits – the latter can be known by applying Newton's laws of motion, though this example involved highly correlated events.

Organized complexity, in Weaver's view, resides in nothing else than the non-random, or correlated, interaction between the parts. These non-random, or correlated, relationships create a differentiated structure which can, as a system, interact with other systems. The coordinated system manifests properties not carried by, or dictated by, individual parts. The organized aspect of this form of complexity vis a vis other systems than the subject system can be said to "emerge," without any "guiding hand."

The number of parts does not have to be very large for a particular system to have emergent properties. A system of organized complexity may be understood in its properties (behavior among the properties) through modeling and simulation, particularly modeling and simulation with computers. An example of organized complexity is a city neighborhood as a living mechanism, with the neighborhood people among the system's parts. [4]

Sources and factors of complexity

The source of disorganized complexity is the large number of parts in the system of interest, and the lack of correlation between elements in the system.

There is no consensus at present on general rules regarding the sources of organized complexity, though the lack of randomness implies correlations between elements. See e.g. Robert Ulanowicz's treatment of ecosystems.[5] Consistent with prior statements here, the number of parts (and types of parts) in the system and the number of relations between the parts would have to be non-trivial – however, there is no general rule to separate "trivial" from "non-trivial".

Complexity of an object or system is a relative property. For instance, for many functions (problems), such a computational complexity as time of computation is smaller when multitape Turing machines are used than when Turing machines with one tape are used. Random Access Machines allow one to even more decrease time complexity (Greenlaw and Hoover 1998: 226), while inductive Turing machines can decrease even the complexity class of a function, language or set (Burgin 2005). This shows that tools of activity can be an important factor of complexity.

Specific meanings of complexity

In several scientific fields, "complexity" has a specific meaning :

- In computational complexity theory, the amounts of resources required for the execution of algorithms is studied. The most popular types of computational complexity are the time complexity of a problem equal to the number of steps that it takes to solve an instance of the problem as a function of the size of the input (usually measured in bits), using the most efficient algorithm, and the space complexity of a problem equal to the volume of the memory used by the algorithm (e.g., cells of the tape) that it takes to solve an instance of the problem as a function of the size of the input (usually measured in bits), using the most efficient algorithm. This allows to classify computational problems by complexity class (such as P, NP ...). An axiomatic approach to computational complexity was developed by Manuel Blum. It allows one to deduce many properties of concrete computational complexity measures, such as time complexity or space complexity, from properties of axiomatically defined measures.
- In algorithmic information theory, the *Kolmogorov complexity* (also called *descriptive complexity*, *algorithmic complexity* or *algorithmic entropy*) of a string is the length of the shortest binary program which outputs that string. Different kinds of Kolmogorov complexity are studied: the uniform complexity, prefix complexity, monotone complexity, time-bounded Kolmogorov complexity, and space-bounded Kolmogorov complexity. An axiomatic approach to Kolmogorov complexity based on Blum axioms (Blum 1967) was introduced by Mark Burgin in the paper presented for publication by Andrey Kolmogorov (Burgin 1982). The axiomatic approach encompasses other approaches to Kolmogorov complexity. It is possible to treat different kinds of Kolmogorov complexity as particular cases of axiomatically defined generalized Kolmogorov complexity. Instead, of proving similar theorems, such as the basic invariance theorem, for each particular measure, it is possible to easily deduce all such results from one corresponding theorem proved in the axiomatic setting. This is a general advantage of the axiomatic approach in mathematics. The axiomatic approach to Kolmogorov complexity was further developed in the book (Burgin 2005) and applied to software metrics (Burgin and Debnath, 2003; Debnath and Burgin, 2003).
- In information processing, complexity is a measure of the total number of properties transmitted by an object and detected by an observer. Such a collection of properties is often referred to as a state.
- In business, complexity describes the variances and their consequences in various fields such as product portfolio, technologies, markets and market segments, locations, manufacturing network, customer portfolio, IT systems, organization, processes etc.
- In physical systems, complexity is a measure of the probability of the state vector of the system. This should not be confused with entropy; it is a distinct mathematical measure, one in which two distinct states are never conflated and considered equal, as is done for the notion of entropy statistical mechanics.
- In mathematics, Krohn-Rhodes complexity is an important topic in the study of finite semigroups and automata.
- In software engineering, programming complexity is a measure of the interactions of the various elements of the software. This differs from the computational complexity described above in that it is a measure of the design of the software.

There are different specific forms of complexity:

- In the sense of how complicated a problem is from the perspective of the person trying to solve it, limits of complexity are measured using a term from cognitive psychology, namely the hrair limit.
- Complex adaptive system denotes systems which have some or all of the following attributes [6]
  - The number of parts (and types of parts) in the system and the number of relations between the parts is non-trivial – however, there is no general rule to separate "trivial" from "non-trivial;"
  - The system has memory or includes feedback;
  - The system can adapt itself according to its history or feedback;

- The relations between the system and its environment are non-trivial or non-linear;
- The system can be influenced by, or can adapt itself to, its environment; and
- The system is highly sensitive to initial conditions.

Study of complexity

Complexity has always been a part of our environment, and therefore many scientific fields have dealt with complex systems and phenomena. Indeed, some would say that only what is somehow complex – what displays variation without being random – is worthy of interest.

The use of the term complex is often confused with the term complicated. In today's systems, this is the difference between myriad connecting "stovepipes" and effective "integrated" solutions.[7] This means that complex is the opposite of independent, while complicated is the opposite of simple.

While this has led some fields to come up with specific definitions of complexity, there is a more recent movement to regroup observations from different fields to study complexity in itself, whether it appears in anthills, human brains, or stock markets. One such interndisciplinary group of fields is relational order theories.

Complexity topics

Complex behaviour

The behaviour of a complex system is often said to be due to emergence and self-organization. Chaos theory has investigated the sensitivity of systems to variations in initial conditions as one cause of complex behaviour.

Complex mechanisms

Recent developments around artificial life, evolutionary computation and genetic algorithms have led to an increasing emphasis on complexity and complex adaptive systems.

Complex simulations

In social science, the study on the emergence of macro-properties from the micro-properties, also known as macro-micro view in sociology. The topic is commonly recognized as social complexity that is often related to the use of computer simulation in social science, i.e.: computational sociology.

Complex systems

Systems theory has long been concerned with the study of complex systems (In recent times, *complexity theory* and *complex systems* have also been used as names of the field). These systems can be biological, economic, technological, etc. Recently, complexity is a natural domain of interest of the real world socio-cognitive systems and emerging systemics research. Complex systems tend to be high-dimensional, non-linear and hard to model. In specific circumstances they may exhibit low dimensional behaviour.

Complexity in data

In information theory, algorithmic information theory is concerned with the complexity of strings of data.

Complex strings are harder to compress. While intuition tells us that this may depend on the codec used to compress a string (a codec could be theoretically created in any arbitrary language, including one in which the very small command "X" could cause the computer to output a very complicated string like '18995316'"), any two Turing-complete languages can be implemented in each other, meaning that the length of two encodings in different languages will vary by at most the length of the "translation" language - which will end up being negligible for sufficiently large data strings.

These algorithmic measures of complexity tend to assign high values to random noise. However, those studying complex systems would not consider randomness as complexity.

Information entropy is also sometimes used in information theory as indicative of complexity.

Applications of complexity

Computational complexity theory is the study of the complexity of problems - that is, the difficulty of solving them. Problems can be classified by complexity class according to the time it takes for an algorithm - usually a computer program - to solve them as a function of the problem size. Some problems are difficult to solve, while others are easy. For example, some difficult problems need algorithms that take an exponential amount of time in terms of the size of the problem to solve. Take the travelling salesman problem, for example. It can be solved in time $O(n^2 2^n)$ (where n is the size of the network to visit - let's say the number of cities the travelling salesman must visit exactly once). As the size of the network of cities grows, the time needed to find the route grows (more than) exponentially.

Even though a problem may be computationally solvable in principle, in actual practice it may not be that simple. These problems might require large amounts of time or an inordinate amount of space. Computational complexity may be approached from many different aspects. Computational complexity can be investigated on the basis of time, memory or other resources used to solve the problem. Time and space are two of the most important and popular considerations when problems of complexity are analyzed.

There exist a certain class of problems that although they are solvable in principle they require so much time or space that it is not practical to attempt to solve them. These problems are called intractable.

There is another form of complexity called hierarchical complexity. It is orthogonal to the forms of complexity discussed so far, which are called horizontal complexity

See also

- Chaos theory
- Command and Control Research Program
- Complexity theory (disambiguation page)
- Cyclomatic complexity
- Evolution of complexity
- Game complexity
- Holism in science
- Interconnectedness
- Model of hierarchical complexity
- Names of large numbers
- Network science
- Network theory
- Occam's razor
- Process architecture
- Programming Complexity
- Sociology and complexity science
- Systems theory
- Variety (cybernetics)
- Volatility, uncertainty, complexity and ambiguity

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External links

- Quantifying Complexity Theory [16] - classification of complex systems
- Complexity Measures [17] - an article about the abundance of not-that-useful complexity measures.
- UC Four Campus Complexity Videoconferences [18] - Human Sciences and Complexity
- Complexity Digest [19] - networking the complexity community
- The Santa Fe Institute [20] - engages in research in complexity related topics
- Exploring Complexity in Science and Technology [21] - A introductory course about complex system by Melanie Mitchell

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[11] http://www.dodccrp.org/files/Smith_Complexity.pdf
[12] http://pespmc1.vub.ac.be/Papers/ELIS-Complexity.pdf
[13] http://jprr.org/index.php/jprr/article/view/117
[14] http://www.jprr.org
[15] http://uk.arxiv.org/abs/nlin.AO/0402023
[16] http://www.calresco.org/lucas/quantify.htm
[17] http://cscs.umich.edu/~crshalizi/notebooks/complexity-measures.html
[18] http://eclectic.ss.uci.edu/~drwhite/center/cac.html
[19] http://comdig.unam.mx/
[20] http://www.santafe.edu/
[21] http://web.cecs.pdx.edu/~mm/ExploringComplexityFall2009/index.html

Nonlinear system

This article describes the use of the term nonlinearity in mathematics. For other meanings, see nonlinearity (disambiguation).

In mathematics, a **nonlinear system** is a system which is not linear, that is, a system which does not satisfy the superposition principle, or whose output is not proportional to its input. Less technically, a nonlinear system is any problem where the variable(s) to be solved for cannot be written as a linear combination of independent components. A nonhomogeneous system, which is linear apart from the presence of a function of the independent variables, is nonlinear according to a strict definition, but such systems are usually studied alongside linear systems, because they can be transformed to a linear system of multiple variables.

Nonlinear problems are of interest to engineers, physicists and mathematicians because most physical systems are inherently nonlinear in nature. Nonlinear equations are difficult to solve and give rise to interesting phenomena such as chaos. The weather is famously nonlinear, where simple changes in one part of the system produce complex effects throughout.

Definition

In mathematics, a linear function (or map) $f(x)$ is one which satisfies both of the following properties:

- additivity, $f(x+y) \ = f(x) \ + f(y)$;
- homogeneity, $f(\alpha x) \ = \alpha f(x)$.

(Additivity implies homogeneity for any rational α, and, for continuous functions, for any real α. For a complex α, homogeneity does not follow from additivity; for example, an antilinear map is additive but not homogeneous.)

An equation written as

$$f(x) = C$$

is called **linear** if $f(x)$ is a linear map (as defined above) and **nonlinear** otherwise. The equation is called *homogeneous* if $C = 0$.

The definition $f(x) = C$ is very general in that x can be any sensible mathematical object (number, vector, function, etc), and the function $f(x)$ can literally be any mapping, including integration or differentiation with associated constraints (such as boundary values). If $f(x)$ contains differentiation of x , the result will be a differential equation.

Nonlinear algebraic equations

Generally, nonlinear algebraic problems are often exactly solvable, and if not they usually can be thoroughly understood through qualitative and numeric analysis. As an example, the equation

$$x^2 + x - 1 = 0$$

may be written as

$$f(x) = C \quad \text{where} \quad f(x) = x^2 + x \quad \text{and} \quad C = 1$$

and is nonlinear because $f(x)$ satisfies neither additivity nor homogeneity (the nonlinearity is due to the x^2). Though nonlinear, this simple example may be solved exactly (via the quadratic formula) and is very well understood. On the other hand, the nonlinear equation

$$x^5 - x - 1 = 0$$

is not exactly solvable (see quintic equation), though it may be qualitatively analyzed and is well understood, for example through making a graph and examining the roots of $f(x) - C = 0$.

Nonlinear recurrence relations

A nonlinear recurrence relation defines successive terms of a sequence as a nonlinear function of preceding terms. Examples of nonlinear recurrence relations are the logistic map and the relations that define the various Hofstadter sequences.

Nonlinear differential equations

A system of differential equations is said to be nonlinear if it is not a linear system. Problems involving nonlinear differential equations are extremely diverse, and methods of solution or analysis are problem dependent. Examples of nonlinear differential equations are the Navier–Stokes equations in fluid dynamics, the Lotka–Volterra equations in biology, and the Black–Scholes PDE in finance.

One of the greatest difficulties of nonlinear problems is that it is not generally possible to combine known solutions into new solutions. In linear problems, for example, a family of linearly independent solutions can be used to construct general solutions through the superposition principle. A good example of this is one-dimensional heat transport with Dirichlet boundary conditions, the solution of which can be written as a time-dependent linear combination of sinusoids of differing frequencies; this makes solutions very flexible. It is often possible to find several very specific solutions to nonlinear equations, however the lack of a superposition principle prevents the construction of new solutions.

Ordinary differential equations

First order ordinary differential equations are often exactly solvable by separation of variables, especially for autonomous equations. For example, the nonlinear equation

$$\frac{\mathrm{d}u}{\mathrm{d}x} = -u^2$$

will easily yield $u = (x + C)^{-1}$ as a general solution. The equation is nonlinear because it may be written as

$$\frac{\mathrm{d}u}{\mathrm{d}x} + u^2 = 0$$

and the left-hand side of the equation is not a linear function of u and its derivatives. Note that if the u^2 term were replaced with u, the problem would be linear (the exponential decay problem).

Second and higher order ordinary differential equations (more generally, systems of nonlinear equations) rarely yield closed form solutions, though implicit solutions and solutions involving nonelementary integrals are encountered.

Common methods for the qualitative analysis of nonlinear ordinary differential equations include:

- Examination of any conserved quantities, especially in Hamiltonian systems.
- Examination of dissipative quantities (see Lyapunov function) analogous to conserved quantities.
- Linearization via Taylor expansion.
- Change of variables into something easier to study.
- Bifurcation theory.
- Perturbation methods (can be applied to algebraic equations too).

Partial differential equations

The most common basic approach to studying nonlinear partial differential equations is to change the variables (or otherwise transform the problem) so that the resulting problem is simpler (possibly even linear). Sometimes, the equation may be transformed into one or more ordinary differential equations, as seen in the similarity transform or separation of variables, which is always useful whether or not the resulting ordinary differential equation(s) is solvable.

Another common (though less mathematic) tactic, often seen in fluid and heat mechanics, is to use scale analysis to simplify a general, natural equation in a certain specific boundary value problem. For example, the (very) nonlinear Navier-Stokes equations can be simplified into one linear partial differential equation in the case of transient, laminar, one dimensional flow in a circular pipe; the scale analysis provides conditions under which the flow is laminar and one dimensional and also yields the simplified equation.

Other methods include examining the characteristics and using the methods outlined above for ordinary differential equations.

Example: pendulum

A classic, extensively studied nonlinear problem is the dynamics of a pendulum under influence of gravity. Using Lagrangian mechanics, it may be shown[1] that the motion of a pendulum can be described by the dimensionless nonlinear equation

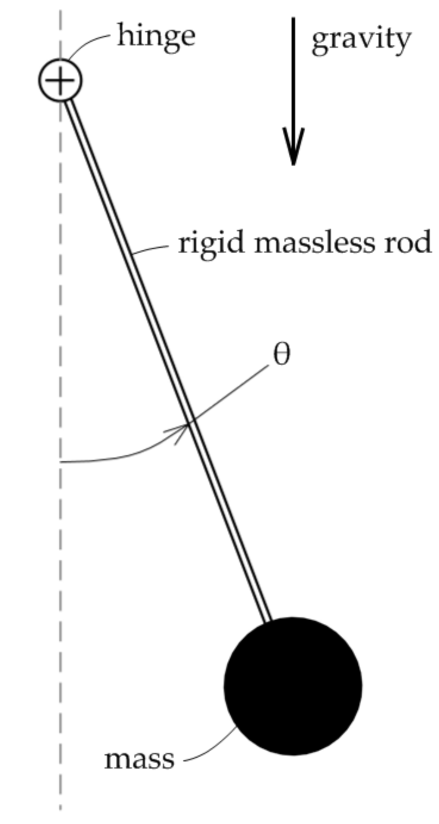
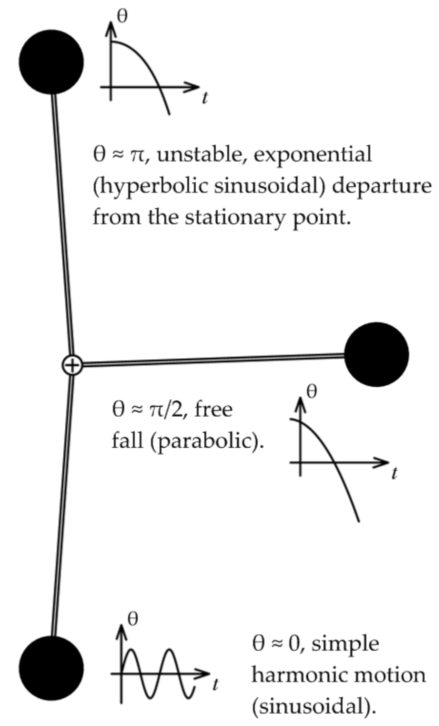


Illustration of a pendulum.



Linearizations of a pendulum.

$$\frac{d^2\theta}{dt^2} + \sin(\theta) = 0$$

where gravity points "downwards" and θ is the angle the pendulum forms with its rest position, as shown in the figure at right. One approach to "solving" this equation is to use $d\theta/dt$ as an integrating factor, which would eventually yield

$$\int \frac{d\theta}{\sqrt{C_0 + 2\cos(\theta)}} = t + C_1$$

which is an implicit solution involving an elliptic integral. This "solution" generally does not have many uses because most of the nature of the solution is hidden in the nonelementary integral (nonelementary even if $C_0 = 0$).

Another way to approach the problem is to linearize any nonlinearities (the sine function term in this case) at the various points of interest through Taylor expansions. For example, the linearization at $\theta = 0$, called the small angle approximation, is

$$\frac{d^2\theta}{dt^2} + \theta = 0$$

since $\sin(\theta) \approx \theta$ for $\theta \approx 0$. This is a simple harmonic oscillator corresponding to oscillations of the pendulum near the bottom of its path. Another linearization would be at $\theta = \pi$, corresponding to the pendulum being straight up:

$$\frac{d^2\theta}{dt^2} + \pi - \theta = 0$$

since $\sin(\theta) \approx \pi - \theta$ for $\theta \approx \pi$. The solution to this problem involves hyperbolic sinusoids, and note that unlike the small angle approximation, this approximation is unstable, meaning that $|\theta|$ will usually grow without limit, though bounded solutions are possible. This corresponds to the difficulty of balancing a pendulum upright, it is literally an unstable state.

One more interesting linearization is possible around $\theta = \pi/2$, around which $\sin(\theta) \approx 1$:

$$\frac{d^2\theta}{dt^2} + 1 = 0.$$

This corresponds to a free fall problem. A very useful qualitative picture of the pendulum's dynamics may be obtained by piecing together such linearizations, as seen in the figure at right. Other techniques may be used to find (exact) phase portraits and approximate periods.

Metaphorical use

Engineers often use the term *nonlinear* to refer to irrational or erratic behavior, with the implication that the person who "goes nonlinear" is on the edge of losing control or even having a nervous breakdown.[2]

Types of nonlinear behaviors

- Indeterminism - the behavior of a system cannot be predicted.
- Multistability - alternating between two or more exclusive states.
- Aperiodic oscillations - functions that do not repeat values after some period (otherwise known as chaotic oscillations or chaos).

Examples of nonlinear equations

- AC power flow model
- Ball and beam system
- Bellman equation for optimal policy
- Boltzmann transport equation
- Colebrook equation
- General relativity
- Ginzburg-Landau equation
- Navier-Stokes equations of fluid dynamics
- Korteweg–de Vries equation
- nonlinear optics
- nonlinear Schrödinger equation
- Richards equation for unsaturated water flow
- Robot unicycle balancing
- Sine-Gordon equation
- Landau-Lifshitz equation
- Ishimori equation
- Van der Pol equation
- Liénard equation
- Vlasov equation

See also the list of non-linear partial differential equations

See also

- Aleksandr Mikhailovich Lyapunov
- Dynamical system
- Volterra series
- Vector soliton

Further reading

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External links

- A collection of non-linear models and demo applets [3] (in Monash University's Virtual Lab)
- Command and Control Research Program (CCRP) [4]
- New England Complex Systems Institute: Concepts in Complex Systems [5]
- Nonlinear Dynamics I: Chaos [6] at MIT's OpenCourseWare [7]
- Nonlinear Models [8] Nonlinear Model Database of Physical Systems (MATLAB)
- The Center for Nonlinear Studies at Los Alamos National Laboratory [9]
- FyDiK [10] Software for simulations of nonlinear dynamical systems

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Kolmogorov complexity

In algorithmic information theory (a subfield of computer science), the **Kolmogorov complexity** of an object, such as a piece of text, is a measure of the computational resources needed to specify the object.

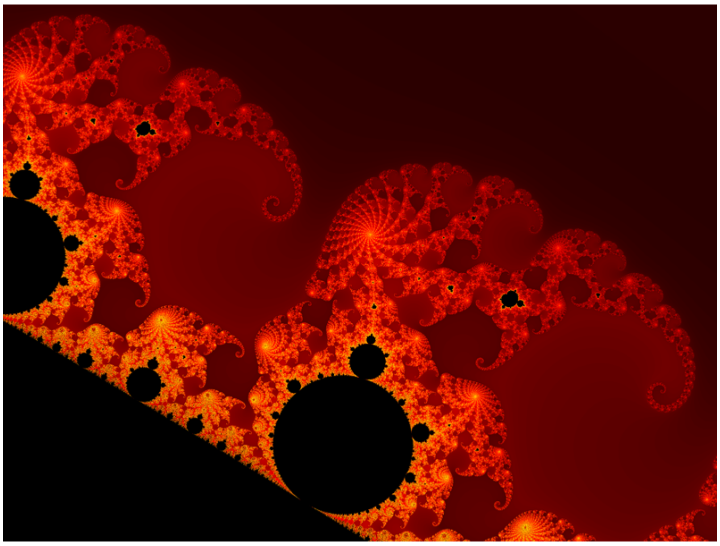
Kolmogorov complexity is also known as **descriptive complexity**, **Kolmogorov-Chaitin complexity**, **stochastic complexity**, **algorithmic entropy**, or **program-size complexity**.

For example, consider the following two strings of length 64, each containing only lowercase letters, numbers, and spaces:

```
abababababababababababababababababababababababababababababababab
4c1j5b2p0cv4w1x8rx2y39umgw5q85s7uraqbjfdppa0q7nieieqe9noc4cvafzf
```

The first string has a short English-language description, namely "ab 32 times", which consists of 11 characters. The second one has no obvious simple description (using the same character set) other than writing down the string itself, which has 64 characters.

More formally, the complexity of a string is the length of the string's shortest description in some fixed universal description language. The sensitivity of complexity relative to the choice of description language is discussed below. It can be shown that the Kolmogorov complexity of any string cannot be too much larger than the length of the string itself. Strings whose Kolmogorov complexity is small relative to the string's size are not considered to be complex. The notion of Kolmogorov complexity is surprisingly deep and can be used to state and prove impossibility results akin to Gödel's incompleteness theorem and Turing's halting problem.


This image illustrates part of the Mandelbrot set fractal. Simply storing the 24-bit color of each pixel in this image would require 1.62 million bits; but a small computer program can reproduce these 1.62 million bits using the definition of the Mandelbrot set. Thus, the Kolmogorov complexity of the raw file encoding this bitmap is much less than 1.62 million.

Definition

To define Kolmogorov complexity, we must first specify a description language for strings. Such a description language can be based on any programming language, such as Lisp, Pascal, or Java Virtual Machine bytecode. If **P** is a program which outputs a string x, then **P** is a description of x. The length of the description is just the length of **P** as a character string. In determining the length of **P**, the lengths of any subroutines used in **P** must be accounted for. The length of any integer constant n which occurs in the program **P** is the number of bits required to represent n, that is (roughly) $\log_2 n$.

We could alternatively choose an encoding for Turing machines, where an *encoding* is a function which associates to each Turing Machine **M** a bitstring **<M>**. If **M** is a Turing Machine which on input w outputs string x, then the concatenated string **<M>** w is a description of x. For theoretical analysis, this approach is more suited for constructing detailed formal proofs and is generally preferred in the research literature. The binary lambda calculus may provide the simplest definition of complexity yet. In this article we will use an informal approach.

Any string s has at least one description, namely the program

```
function GenerateFixedString()
   return s
```

If a description of s, $d(s)$, is of minimal length—i.e. it uses the fewest number of characters—it is called a **minimal description** of s. Then the length of $d(s)$—i.e. the number of characters in the description—is the **Kolmogorov complexity** of s, written $K(s)$. Symbolically,

$$K(s) = |d(s)|.$$

We now consider how the choice of description language affects the value of K and show that the effect of changing the description language is bounded.

Theorem. If K_1 and K_2 are the complexity functions relative to description languages L_1 and L_2, then there is a constant c (which depends only on the languages L_1 and L_2) such that

$$\forall s \ |K_1(s) - K_2(s)| \leq c.$$

Proof. By symmetry, it suffices to prove that there is some constant c such that for all bitstrings s,

$$K_1(s) \leq K_2(s) + c.$$

To see why this is so, suppose there is a program in the language L_1 which acts as an interpreter for L_2:

```
function InterpretLanguage(string p)
```

where p is a program in L_2. The interpreter is characterized by the following property:

Running InterpretLanguage on input p returns the result of running p.

Thus if **P** is a program in L_2 which is a minimal description of s, then InterpretLanguage(**P**) returns the string s. The length of this description of s is the sum of

1. The length of the program InterpretLanguage, which we can take to be the constant c.
2. The length of **P** which by definition is $K_2(s)$.

This proves the desired upper bound.

See also invariance theorem.

History and context

Algorithmic information theory is the area of computer science that studies Kolmogorov complexity and other complexity measures on strings (or other data structures).

The concept and theory of Kolmogorov Complexity is based on a crucial theorem first discovered by Ray Solomonoff who published it in 1960, describing it in "A Preliminary Report on a General Theory of Inductive Inference" (see ref) as part of his invention of Algorithmic Probability. He gave a more complete description in his 1964 publications, "A Formal Theory of Inductive Inference," Part 1 and Part 2 in *Information and Control* (see ref).

Andrey Kolmogorov later independently published this theorem in *Problems Inform. Transmission*, 1, (1965), 1-7. Gregory Chaitin also presents this theorem in J. ACM, 16 (1969). Chaitin's paper was submitted October 1966, revised in December 1968 and cites both Solomonoff's and Kolmogorov's papers.

The theorem says that among algorithms that decode strings from their descriptions (codes) there exists an optimal one. This algorithm, for all strings, allows codes as short as allowed by any other algorithm up to an additive constant that depends on the algorithms, but not on the strings themselves. Solomonoff used this algorithm, and the code lengths it allows, to define a string's `universal probability' on which inductive inference of a string's subsequent digits can be based. Kolmogorov used this theorem to define several functions of strings: complexity, randomness, and information.

When Kolmogorov became aware of Solomonoff's work, he acknowledged Solomonoff's priority (IEEE Trans. Inform Theory, 14:5(1968), 662-664). For several years, Solomonoff's work was better known in the Soviet Union

than in the Western World. The general consensus in the scientific community, however, was to associate this type of complexity with Kolmogorov, who was concerned with randomness of a sequence while Algorithmic Probability became associated with Solomonoff, who focused on prediction using his invention of the universal a priori probability distribution.

There are several other variants of Kolmogorov complexity or algorithmic information. The most widely used one is based on self-delimiting programs and is mainly due to Leonid Levin (1974).

An axiomatic approach to Kolmogorov complexity based on Blum axioms (Blum 1967) was introduced by Mark Burgin in the paper presented for publication by Andrey Kolmogorov (Burgin 1982). This approach was further developed in the book (Burgin 2005) and applied to software metrics (Burgin and Debnath, 2003; Debnath and Burgin, 2003).

Naming this concept "Kolmogorov complexity" is an example of the Matthew effect.

Basic results

In the following, we will fix one definition and simply write $K(s)$ for the complexity of the string s.

It is not hard to see that the minimal description of a string cannot be too much larger than the string itself: the program GenerateFixedString above that outputs s is a fixed amount larger than s.

Theorem. There is a constant c such that

$$\forall s \ K(s) \leq |s| + c.$$

Incomputability of Kolmogorov complexity

The first result is that there is no way to effectively compute K.

Theorem. K is not a computable function.

In other words, there is no program which takes a string s as input and produces the integer $K(s)$ as output. We show this by contradiction by making a program that creates a string that should only be able to be created by a longer program. Suppose there is a program

```
function KolmogorovComplexity(string s)
```

that takes as input a string s and returns $K(s)$. Now consider the program

```
function GenerateComplexString(int n)
   for i = 1 to infinity:
      for each string s of length exactly i
         if KolmogorovComplexity(s) >= n
            return s
            quit
```

This program calls KolmogorovComplexity as a subroutine. This program tries every string, starting with the shortest, until it finds a string with complexity at least n, then returns that string. Therefore, given any positive integer n, it produces a string with Kolmogorov complexity at least as great as n. The program itself has a fixed length U. The input to the program GenerateComplexString is an integer n; here, the size of n is measured by the number of bits required to represent n which is $\log_2(n)$. Now consider the following program:

```
function GenerateParadoxicalString()
    return GenerateComplexString(n0)
```

This program calls GenerateComplexString as a subroutine and also has a free parameter n_0. This program outputs a string s whose complexity is at least n_0. By an auspicious choice of the parameter n_0 we will arrive at a contradiction.

To choose this value, note *s* is described by the program GenerateParadoxicalString whose length is at most

$$U + \log_2(n_0) + C$$

where *C* is the "overhead" added by the program GenerateParadoxicalString. Since *n* grows faster than $\log_2(n)$, there exists a value n_0 such that

$$U + \log_2(n_0) + C < n_0.$$

But this contradicts the definition of having a complexity at least n_0. That is, by the definition of *K*(*s*), the string *s* returned by GenerateParadoxicalString is only supposed to be able to be generated by a program of length n_0 or longer, but GenerateParadoxicalString is shorter than n_0. Thus the program named "KolmogorovComplexity" cannot actually computably find the complexity of arbitrary strings.

This is proof by contradiction where the contradiction is similar to the Berry paradox: "Let *n* be the smallest positive integer that cannot be defined in fewer than twenty English words." It is also possible to show the uncomputability of K by reduction from the uncomputability of the halting problem H, since K and H are Turing-equivalent.[1]

In the programming languages community there is a corollary known as the Full employment theorem, stating there is no perfect size-optimizing compiler.

Chain rule for Kolmogorov complexity

The chain rule for Kolmogorov complexity states that

$$K(X,Y) = K(X) + K(Y|X) + O(\log(K(X,Y))).$$

It states that the shortest program that reproduces *X* and *Y* is no more than a logarithmic term larger than a program to reproduce *X* and a program to reproduce *Y* given *X*. Using this statement one can define an analogue of mutual information for Kolmogorov complexity.

Compression

It is straightforward to compute upper bounds for $K(s)$: simply compress the string s with some method, implement the corresponding decompressor in the chosen language, concatenate the decompressor to the compressed string, and measure the resulting string's length.

A string *s* is compressible by a number *c* if it has a description whose length does not exceed $|s| - c$. This is equivalent to saying $K(s) \leq |s| - c$. Otherwise *s* is incompressible by *c*. A string incompressible by 1 is said to be simply *incompressible*; by the pigeonhole principle, incompressible strings must exist, since there are 2^n bit strings of length *n* but only $2^n - 1$ shorter strings, that is strings of length $n - 1$ or less.

For the same reason, most strings are complex in the sense that they cannot be significantly compressed: $K(s)$ is not much smaller than $|s|$, the length of *s* in bits. To make this precise, fix a value of *n*. There are 2^n bitstrings of length *n*. The uniform probability distribution on the space of these bitstrings assigns exactly equal weight 2^{-n} to each string of length *n*.

Theorem. With the uniform probability distribution on the space of bitstrings of length *n*, the probability that a string is incompressible by *c* is at least $1 - 2^{-c+1} + 2^{-n}$.

To prove the theorem, note that the number of descriptions of length not exceeding $n - c$ is given by the geometric series:

$$1 + 2 + 2^2 + \cdots + 2^{n-c} = 2^{n-c+1} - 1$$

There remain at least

$$2^n - 2^{n-c+1} + 1$$

many bitstrings of length *n* that are incompressible by *c*. To determine the probability divide by 2^n.

This theorem is the justification for various challenges in comp.compression FAQ [2]. Despite this result, it is sometimes claimed by certain individuals (considered cranks) that they have produced algorithms which uniformly compress data without loss. See lossless data compression.

Chaitin's incompleteness theorem

We know that, in the set of all possible strings, most strings are complex in the sense that they cannot be described in any significantly "compressed" way. However, it turns out that the fact that a specific string is complex cannot be formally proved, if the string's length is above a certain threshold. The precise formalization is as follows. First fix a particular axiomatic system **S** for the natural numbers. The axiomatic system has to be powerful enough so that to certain assertions **A** about complexity of strings one can associate a formula $\mathbf{F_A}$ in **S**. This association must have the following property: if $\mathbf{F_A}$ is provable from the axioms of **S**, then the corresponding assertion **A** is true. This "formalization" can be achieved either by an artificial encoding such as a Gödel numbering or by a formalization which more clearly respects the intended interpretation of **S**.

Theorem. There exists a constant *L* (which only depends on the particular axiomatic system and the choice of description language) such that there does not exist a string *s* for which the statement

$$K(s) \geq L$$

(as formalized in **S**) can be proven within the axiomatic system **S**.

Note that by the abundance of nearly incompressible strings, the vast majority of those statements must be true.

The proof of this result is modeled on a self-referential construction used in Berry's paradox. The proof is by contradiction. If the theorem were false, then

> **Assumption (X)**: For any integer n there exists a string s for which there is a proof in **S** of the formula "$K(s) \geq n$" (which we assume can be formalized in **S**).

We can find an effective enumeration of all the formal proofs in **S** by some procedure

```
function NthProof(int n)
```

which takes as input n and outputs some proof. This function enumerates all proofs. Some of these are proofs for formulas we do not care about here (examples of proofs which will be listed by the procedure NthProof are the various known proofs of the law of quadratic reciprocity, those of Fermat's little theorem or the proof of Fermat's last theorem all translated into the formal language of **S**). Some of these are complexity formulas of the form $K(s) \geq n$ where s and n are constants in the language of **S**. There is a program

```
  function NthProofProvesComplexityFormula(int n)
```

which determines whether the n^{th} proof actually proves a complexity formula $K(s) \geq L$. The strings s and the integer L in turn are computable by programs:

```
  function StringNthProof(int n)
```

```
  function ComplexityLowerBoundNthProof(int n)
```

Consider the following program

```
  function GenerateProvablyComplexString(int n)
     for i = 1 to infinity:
        if  NthProofProvesComplexityFormula(i) and
ComplexityLowerBoundNthProof(i) ≥ n
           return StringNthProof(i)
           quit
```

Given an n, this program tries every proof until it finds a string and a proof in the formal system **S** of the formula $K(s) \geq L$ for some $L \geq n$. The program terminates by our **Assumption (X)**. Now this program has a length U. There is an integer n_0 such that $U + \log_2(n_0) + C < n_0$, where C is the overhead cost of

```
function GenerateProvablyParadoxicalString()
   return GenerateProvablyComplexString(n0)
   quit
```

The program GenerateProvablyParadoxicalString outputs a string s for which there exists an L such that $K(s) \geq L$ can be formally proved in **S** with $L \geq n_0$. In particular $K(s) \geq n_0$ is true. However, s is also described by a program of length $U + \log_2(n_0) + C$ so its complexity is less than n_0. This contradiction proves **Assumption (X)** cannot hold.

Similar ideas are used to prove the properties of Chaitin's constant.

Minimum message length

The minimum message length principle of statistical and inductive inference and machine learning was developed by C.S. Wallace and D.M. Boulton in 1968. MML is Bayesian (it incorporates prior beliefs) and information-theoretic. It has the desirable properties of statistical invariance (the inference transforms with a re-parametrisation, such as from polar coordinates to Cartesian coordinates), statistical consistency (even for very hard problems, MML will converge to any underlying model) and efficiency (the MML model will converge to any true underlying model about as quickly as is possible). C.S. Wallace [3] and D.L. Dowe showed a formal connection between MML and algorithmic information theory (or Kolmogorov complexity) in 1999.

Kolmogorov randomness

Kolmogorov randomness (also called *algorithmic randomness*) defines a string (usually of bits) as being random if and only if it is shorter than any computer program that can produce that string. This definition of randomness is critically dependent on the definition of Kolmogorov complexity. To make this definition complete, a computer has to be specified, usually a Turing machine. According to the above definition of randomness, a random string is also an "incompressible" string, in the sense that it is impossible to give a representation of the string using a program whose length is shorter than the length of the string itself. However, according to this definition, most strings shorter than a certain length end up to be (Chaitin-Kolmogorovically) random because the best one can do with very small strings is to write a program that simply prints these strings.

See also

- Berlekamp–Massey algorithm
- Data compression
- Inductive inference
- Important publications in algorithmic information theory
- Levenshtein distance
- Grammar induction

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External links

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Gödel's incompleteness theorems

Gödel's incompleteness theorems are two theorems of mathematical logic that establish inherent limitations of all but the most trivial axiomatic systems for mathematics. The theorems, proven by Kurt Gödel in 1931, are important both in mathematical logic and in the philosophy of mathematics. The two results are widely interpreted as showing that Hilbert's program to find a complete and consistent set of axioms for all of mathematics is impossible, thus giving a negative answer to Hilbert's second problem.

The first incompleteness theorem states that no consistent system of axioms whose theorems can be listed by an "effective procedure" (essentially, a computer program) is capable of proving all facts about the natural numbers. For any such system, there will always be statements about the natural numbers that are true, but that are unprovable within the system. The second incompleteness theorem shows that if such a system is also capable of proving certain basic facts about the natural numbers, then one particular arithmetic truth the system cannot prove is the consistency of the system itself.

Background

In mathematical logic, a theory is a set of sentences expressed in a formal language. Some statements in a theory are included without proof (these are the axioms of the theory), and others (the theorems) are included because they are implied by the axioms.

Because statements of a formal theory are written in symbolic form, it is possible to mechanically verify that a formal proof from a finite set of axioms is valid. This task, known as automatic proof verification, is closely related to automated theorem proving; the difference is that instead of constructing a new proof, the proof verifier simply checks that a provided formal proof (or, in some cases, instructions that can be followed to create a formal proof) is correct. This is not merely hypothetical; systems such as Isabelle are used today to formalize proofs and then check their validity.

Many theories of interest include an infinite set of axioms, however. To verify a formal proof when the set of axioms is infinite, it must be possible to determine whether a statement that is claimed to be an axiom is actually an axiom. This issue arises in first order theories of arithmetic, such as Peano arithmetic, because the principle of mathematical induction is expressed as an infinite set of axioms (an axiom schema).

A formal theory is said to be *effectively generated* if its set of axioms is a recursively enumerable set. This means that there is a computer program that, in principle, could enumerate all the axioms of the theory without listing any statements that are not axioms. This is equivalent to the ability to enumerate all the theorems of the theory without enumerating any statements that are not theorems. For example, each of the theories of Peano arithmetic and Zermelo–Fraenkel set theory has an infinite number of axioms and each is effectively generated.

In choosing a set of axioms, one goal is to be able to prove as many correct results as possible, without proving any incorrect results. A set of axioms is complete if, for any statement in the axioms' language, either that statement or its negation is provable from the axioms. A set of axioms is (simply) consistent if there is no statement such that both the statement and its negation are provable from the axioms. In the standard system of first-order logic, an inconsistent set of axioms will prove every statement in its language (this is sometimes called the principle of explosion), and is thus automatically complete. A set of axioms that is both complete and consistent, however, proves a maximal set of non-contradictory theorems. Gödel's incompleteness theorems show that in certain cases it is not possible to obtain an effectively generated, complete, consistent theory.

First incompleteness theorem

Gödel's first incompleteness theorem states that:

> Any effectively generated theory capable of expressing elementary arithmetic cannot be both consistent and complete. In particular, for any consistent, effectively generated formal theory that proves certain basic arithmetic truths, there is an arithmetical statement that is true,[1] but not provable in the theory (Kleene 1967, p. 250).

The true but unprovable statement referred to by the theorem is often referred to as “the Gödel sentence” for the theory. It is not unique; there are infinitely many statements in the language of the theory that share the property of being true but unprovable.[2]

For each consistent formal theory *T* having the required small amount of number theory, the corresponding Gödel sentence *G* asserts: “*G* cannot be proved to be true within the theory *T*”. If *G* were provable under the axioms and rules of inference of *T*, then *T* would have a theorem, *G*, which effectively contradicts itself, and thus the theory *T* would be inconsistent. This means that if the theory *T* is consistent then *G* cannot be proved within it. This means that *G*'s claim about its own unprovability is correct; in this sense *G* is not only unprovable but true. Thus provability-within-the-theory-*T* is not the same as truth; the theory *T* is incomplete.

If *G* is true: *G* cannot be proved within the theory, and the theory is incomplete. If *G* is false: then *G* can be proved within the theory and then the theory is inconsistent, since *G* is both provable and refutable from *T*.

Each theory has its own Gödel statement. It is possible to define a larger theory *T’* that contains the whole of *T*, plus *G* as an additional axiom. This will not result in a complete theory, because Gödel's theorem will also apply to *T’*, and thus *T’* cannot be complete. In this case, *G* is indeed a theorem in *T’*, because it is an axiom. Since *G* states only that it is not provable in *T*, no contradiction is presented by its provability in *T’*. However, because the incompleteness theorem applies to *T’*: there will be a new Gödel statement *G’* for *T’*, showing that *T’* is also incomplete. *G’* will differ from *G* in that *G’* will refer to *T’*, rather than *T*.

To prove the first incompleteness theorem, Gödel represented statements by numbers. Then the theory at hand, which is assumed to prove certain facts about numbers, also proves facts about its own statements. Questions about the provability of statements are represented as questions about the properties of numbers, which would be decidable by the theory if it were complete. In these terms, the Gödel sentence states that no natural number exists with a certain, strange property. A number with this property would encode a proof of the inconsistency of the theory. If there were such a number then the theory would be inconsistent, contrary to the consistency hypothesis. So, under the assumption that the theory is consistent, there is no such number.

Meaning of the first incompleteness theorem

Gödel's first incompleteness theorem shows that any consistent formal system that includes enough of the theory of the natural numbers is incomplete; there are true statements expressible in its language that are unprovable. Thus no formal system (satisfying the hypotheses of the theorem) that aims to characterize the natural numbers can actually do so, as there will be true number-theoretical statements which that system cannot prove. This fact is sometimes thought to have severe consequences for the program of logicism proposed by Gottlob Frege and Bertrand Russell, which aimed to define the natural numbers in terms of logic (Hellman 1981, p. 451–468). Some (like Bob Hale and Crispin Wright) believe that it is not a problem for logicism because the incompleteness theorems apply equally to second order logic as they do to arithmetic. It is only those who believe that the natural numbers are to be defined in terms of first order logic—which is consistent and complete—who have this problem.

The existence of an incomplete formal system is in itself not particularly surprising. A system may be incomplete simply because not all the necessary axioms have been discovered. For example, Euclidean geometry without the parallel postulate is incomplete; it is not possible to prove or disprove the parallel postulate from the remaining axioms.

Gödel's theorem shows that, in theories that include a small portion of number theory, a complete and consistent finite list of axioms can *never* be created, nor even an infinite list that can be enumerated by a computer program. Each time a new statement is added as an axiom, there are other true statements that still cannot be proved, even with the new axiom. If an axiom is ever added that makes the system complete, it does so at the cost of making the system inconsistent.

It *is* possible to have a complete and consistent list of axioms that *cannot* be enumerated by a computer program. For example, one might take all true statements about the natural numbers to be axioms (and no false statements). But then there is no mechanical way to decide, given a statement about the natural numbers, whether it is an axiom or not, and thus no effective way to verify a formal proof in this theory.

Many logicians believe that Gödel's incompleteness theorems struck a fatal blow to David Hilbert's second problem, which asked for a finitary consistency proof for mathematics. The second incompleteness theorem, in particular, is often viewed as making the problem impossible. Not all mathematicians agree with this analysis, however, and the status of Hilbert's second problem is not yet decided (see "Modern viewpoints on the status of the problem").

Relation to the liar paradox

The liar paradox is the sentence "This sentence is false." An analysis of the liar sentence shows that it cannot be true (for then, as it asserts, it is false), nor can it be false (for then, it is true). A Gödel sentence G for a theory T makes a similar assertion to the liar sentence, but with truth replaced by provability: G says "G is not provable in the theory T." The analysis of the truth and provability of G is a formalized version of the analysis of the truth of the liar sentence.

It is not possible to replace "not provable" with "false" in a Gödel sentence because the predicate "Q is the Gödel number of a false formula" cannot be represented as a formula of arithmetic. This result, known as Tarski's undefinability theorem, was discovered independently by Gödel (when he was working on the proof of the incompleteness theorem) and by Alfred Tarski.

Original statements

The first incompleteness theorem first appeared as "Theorem VI" in Gödel's 1931 paper *On Formally Undecidable Propositions in Principia Mathematica and Related Systems I.* The second incompletness theorem appeared as "Theorem XI" in the same paper.

Extensions of Gödel's original result

Gödel demonstrated the incompleteness of the theory of *Principia Mathematica*, a particular theory of arithmetic, but a parallel demonstration could be given for any effective theory of a certain expressiveness. Gödel commented on this fact in the introduction to his paper, but restricted the proof to one system for concreteness. In modern statements of the theorem, it is common to state the effectiveness and expressiveness conditions as hypotheses for the incompleteness theorem, so that it is not limited to any particular formal theory. The terminology used to state these conditions was not yet developed in 1931 when Gödel published his results.

Gödel's original statement and proof of the incompleteness theorem requires the assumption that the theory is not just consistent but *ω-consistent*. A theory is **ω-consistent** if it is not ω-inconsistent, and is ω-inconsistent if there is a predicate P such that for every specific natural number n the theory proves $\sim P(n)$, and yet the theory also proves that there exists a natural number n such that $P(n)$. That is, the theory says that a number with property P exists while denying that it has any specific value. The ω-consistency of a theory implies its consistency, but consistency does not imply ω-consistency. J. Barkley Rosser (1936) strengthened the incompleteness theorem by finding a variation of the proof (Rosser's trick) that only requires the theory to be consistent, rather than ω-consistent. This is mostly of technical interest, since all true formal theories of arithmetic (theories whose axioms are all true statements about natural numbers) are ω-consistent, and thus Gödel's theorem as originally stated applies to them. The stronger version of the incompleteness theorem that only assumes consistency, rather than ω-consistency, is now commonly known as Gödel's incompleteness theorem and as the Gödel–Rosser theorem.

Second incompleteness theorem

Gödel's second incompleteness theorem can be stated as follows:

> For any formal effectively generated theory *T* including basic arithmetical truths and also certain truths about formal provability, *T* includes a statement of its own consistency if and only if *T* is inconsistent.

This strengthens the first incompleteness theorem, because the statement constructed in the first incompleteness theorem does not directly express the consistency of the theory. The proof of the second incompleteness theorem is obtained, essentially, by formalizing the proof of the first incompleteness theorem within the theory itself.

A technical subtlety in the second incompleteness theorem is how to express the consistency of *T* as a formula in the language of *T*. There are many ways to do this, and not all of them lead to the same result. In particular, different formalizations of the claim that *T* is consistent may be inequivalent in *T*, and some may even be provable. For example, first-order Peano arithmetic (PA) can prove that the largest consistent subset of PA is consistent. But since PA is consistent, the largest consistent subset of PA is just PA, so in this sense PA "proves that it is consistent". What PA does not prove is that the largest consistent subset of PA is, in fact, the whole of PA. (The term "largest consistent subset of PA" is rather vague, but what is meant here is the largest consistent initial segment of the axioms of PA ordered according to some criteria; for example, by "Gödel numbers", the numbers encoding the axioms as per the scheme used by Gödel mentioned above).

In the case of Peano arithmetic, or any familiar explicitly axiomatized theory *T*, it is possible to canonically define a formula Con(*T*) expressing the consistency of *T*; this formula expresses the property that "there does not exist a natural number coding a sequence of formulas, such that each formula is either one of the axioms of *T*, a logical axiom, or an immediate consequence of preceding formulas according to the rules of inference of first-order logic, and such that the last formula is a contradiction".

The formalization of Con(T) depends on two factors: formalizing the notion of a sentence being derivable from a set of sentences and formalizing the notion of being an axiom of T. Formalizing derivability can be done in canonical fashion: given an arithmetical formula A(x) defining a set of axioms, one can canonically form a predicate $\mathrm{Prov}_A(P)$ which expresses that P is provable from the set of axioms defined by A(x). In addition, $\mathrm{Prov}_A(P)$ must satisfy the so-called Hilbert–Bernays provability conditions:

1. If T proves P, then T proves $\mathrm{Prov}_A(P)$.
2. T proves 1.; that is, T proves that if T proves P, then T proves $\mathrm{Prov}_A(P)$.
3. T proves that if T proves that ($P \rightarrow Q$) then T proves that provability of P implies provability of Q.

Implications for consistency proofs

Gödel's second incompleteness theorem also implies that a theory T_1 satisfying the technical conditions outlined above cannot prove the consistency of any theory T_2 which proves the consistency of T_1. This is because such a theory T_1 can prove that if T_2 proves the consistency of T_1, then T_1 is in fact consistent. For the claim that T_1 is consistent has form "for all numbers n, n has the decidable property of not being a code for a proof of contradiction in T_1". If T_1 were in fact inconsistent, then T_2 would prove for some n that n is the code of a contradiction in T_1. But if T_2 also proved that T_1 is consistent (that is, that there is no such n), then it would itself be inconsistent. This reasoning can be formalized in T_1 to show that if T_2 is consistent, then T_1 is consistent. Since, by second incompleteness theorem, T_1 does not prove its consistency, it cannot prove the consistency of T_2 either.

This corollary of the second incompleteness theorem shows that there is no hope of proving, for example, the consistency of Peano arithmetic using any finitistic means that can be formalized in a theory the consistency of which is provable in Peano arithmetic. For example, the theory of primitive recursive arithmetic (PRA), which is widely accepted as an accurate formalization of finitistic mathematics, is provably consistent in PA. Thus PRA cannot prove the consistency of PA. This fact is generally seen to imply that Hilbert's program, which aimed to justify the use of "ideal" (infinitistic) mathematical principles in the proofs of "real" (finitistic) mathematical statements by giving a finitistic proof that the ideal principles are consistent, cannot be carried out.

The corollary also indicates the epistemological relevance of the second incompleteness theorem. As Georg Kreisel remarked, it would actually provide no interesting information if a theory T proved its consistency. This is because inconsistent theories prove everything, including their consistency. Thus a consistency proof of T in T would give us no clue as to whether T really is consistent; no doubts about the consistency of T would be resolved by such a consistency proof. The interest in consistency proofs lies in the possibility of proving the consistency of a theory T in some theory T' which is in some sense less doubtful than T itself, for example weaker than T. For many naturally occurring theories T and T', such as T = Zermelo–Fraenkel set theory and T' = primitive recursive arithmetic, the consistency of T' is provable in T, and thus T' can't prove the consistency of T by the above corollary of the second incompleteness theorem.

The second incompleteness theorem does not rule out consistency proofs altogether, only consistency proofs that could be formalized in the theory that is proved consistent. For example, Gerhard Gentzen proved the consistency of Peano arithmetic (PA) using the assumption that a certain ordinal called ε_0 is actually wellfounded; see Gentzen's consistency proof. Gentzen's theorem spurred the development of ordinal analysis in proof theory.

Examples of undecidable statements

There are two distinct senses of the word "undecidable" in mathematics and computer science. The first of these is the proof-theoretic sense used in relation to Gödel's theorems, that of a statement being neither provable nor refutable in a specified deductive system. The second sense, which will not be discussed here, is used in relation to computability theory and applies not to statements but to decision problems, which are countably infinite sets of questions each requiring a yes or no answer. Such a problem is said to be undecidable if there is no computable function that correctly answers every question in the problem set (see undecidable problem).

Because of the two meanings of the word undecidable, the term independent is sometimes used instead of undecidable for the "neither provable nor refutable" sense. The usage of "independent" is also ambiguous, however. Some use it to mean just "not provable", leaving open whether an independent statement might be refuted.

Undecidability of a statement in a particular deductive system does not, in and of itself, address the question of whether the truth value of the statement is well-defined, or whether it can be determined by other means. Undecidability only implies that the particular deductive system being considered does not prove the truth or falsity of the statement. Whether there exist so-called "absolutely undecidable" statements, whose truth value can never be known or is ill-specified, is a controversial point in the philosophy of mathematics.

The combined work of Gödel and Paul Cohen has given two concrete examples of undecidable statements (in the first sense of the term): The continuum hypothesis can neither be proved nor refuted in ZFC (the standard axiomatization of set theory), and the axiom of choice can neither be proved nor refuted in ZF (which is all the ZFC axioms *except* the axiom of choice). These results do not require the incompleteness theorem. Gödel proved in 1940 that neither of these statements could be disproved in ZF or ZFC set theory. In the 1960s, Cohen proved that neither is provable from ZF, and the continuum hypothesis cannot be proven from ZFC.

In 1973, the Whitehead problem in group theory was shown to be undecidable, in the first sense of the term, in standard set theory.

In 1977, Paris and Harrington proved that the Paris-Harrington principle, a version of the Ramsey theorem, is undecidable in the first-order axiomatization of arithmetic called Peano arithmetic, but can be proven to be true in the larger system of second-order arithmetic. Kirby and Paris later showed Goodstein's theorem, a statement about sequences of natural numbers somewhat simpler than the Paris-Harrington principle, to be undecidable in Peano arithmetic.

Kruskal's tree theorem, which has applications in computer science, is also undecidable from Peano arithmetic but provable in set theory. In fact Kruskal's tree theorem (or its finite form) is undecidable in a much stronger system codifying the principles acceptable on the basis of a philosophy of mathematics called predicativism. The related but more general graph minor theorem (2003) has consequences for computational complexity theory.

Gregory Chaitin produced undecidable statements in algorithmic information theory and proved another incompleteness theorem in that setting. Chaitin's theorem states that for any theory that can represent enough arithmetic, there is an upper bound c such that no specific number can be proven in that theory to have Kolmogorov complexity greater than c. While Gödel's theorem is related to the liar paradox, Chaitin's result is related to Berry's paradox.

Limitations of Gödel's theorems

The conclusions of Gödel's theorems only hold for the formal theories that satisfy the necessary hypotheses. Not all axiom systems satisfy these hypotheses, even when these systems have models that include the natural numbers as a subset. For example, there are first-order axiomatizations of Euclidean geometry, of real closed fields, and of arithmetic in which multiplication is not *provably* total; none of these meet the hypotheses of Gödel's theorems. The key fact is that these axiomatizations are not expressive enough to define the set of natural numbers or develop basic properties of the natural numbers. Regarding the third example, Dan E. Willard (Willard 2001) has studied many weak systems of arithmetic which do not satisfy the hypotheses of the second incompleteness theorem, and which are consistent and capable of proving their own consistency (see self-verifying theories).

Gödel's theorems only apply to effectively generated (that is, recursively enumerable) theories. If all true statements about natural numbers are taken as axioms for a theory, then this theory is a consistent, complete extension of Peano arithmetic (called true arithmetic) for which none of Gödel's theorems hold, because this theory is not recursively enumerable.

The second incompleteness theorem only shows that the consistency of certain theories cannot be proved from the axioms of those theories themselves. It does not show that the consistency cannot be proved from other (consistent) axioms. For example, the consistency of the Peano arithmetic can be proved in Zermelo–Fraenkel set theory (ZFC), or in theories of arithmetic augmented with transfinite induction, as in Gentzen's consistency proof.

Relationship with computability

The incompleteness theorem is closely related to several results about undecidable sets in recursion theory.

Stephen Cole Kleene (1943) presented a proof of Gödel's incompleteness theorem using basic results of computability theory. One such result shows that the halting problem is unsolvable: there is no computer program that can correctly determine, given a program *P* as input, whether *P* eventually halts when run with no input. Kleene showed that the existence of a complete effective theory of arithmetic with certain consistency properties would force the halting problem to be decidable, a contradiction. This method of proof has also been presented by Shoenfield (1967, p. 132); Charlesworth (1980); and Hopcroft and Ullman (1979).

Franzén (2005, p. 73) explains how Matiyasevich's solution to Hilbert's 10th problem can be used to obtain a proof to Gödel's first incompleteness theorem. Matiyasevich proved that there is no algorithm that, given a multivariate polynomial $p(x_1, x_2,...,x_k)$ with integer coefficients, determines whether there is an integer solution to the equation $p = 0$. Because polynomials with integer coefficients, and integers themselves, are directly expressible in the language of arithmetic, if a multivariate integer polynomial equation $p = 0$ does have a solution in the integers then any sufficiently strong theory of arithmetic *T* will prove this. Moreover, if the theory *T* is ω-consistent, then it will never prove that some polynomial equation has a solution when in fact there is no solution in the integers. Thus, if *T* were complete and ω-consistent, it would be possible to algorithmically determine whether a polynomial equation has a solution by merely enumerating proofs of *T* until either "*p* has a solution" or "*p* has no solution" is found, in contradiction to Matiyasevich's theorem.

Smorynski (1977, p. 842) shows how the existence of recursively inseparable sets can be used to prove the first incompleteness theorem. This proof is often extended to show that systems such as Peano arithmetic are essentially undecidable (see Kleene 1967, p. 274).

Proof sketch for the first theorem

Throughout the proof we assume a formal system is fixed and satisfies the necessary hypotheses. The proof has three essential parts. The first part is to show that statements can be represented by natural numbers, known as Gödel numbers, and that properties of the statements can be detected by examining their Gödel numbers. This part culminates in the construction of a formula expressing the idea that a statement is provable in the system. The second part of the proof is to construct a particular statement that, essentially, says that it is unprovable. The third part of the proof is to analyze this statement to show that it is neither provable nor disprovable in the system.

Arithmetization of syntax

The main problem in fleshing out the proof described above is that it seems at first that to construct a statement *p* that is equivalent to "*p* cannot be proved", *p* would have to somehow contain a reference to *p*, which could easily give rise to an infinite regress. Gödel's ingenious trick, which was later used by Alan Turing in his work on the Entscheidungsproblem, is to represent statements as numbers, which is often called the arithmetization of syntax. This allows a self-referential formula to be constructed in a way that avoids any infinite regress of definitions.

To begin with, every formula or statement that can be formulated in our system gets a unique number, called its **Gödel number**. This is done in such a way that it is easy to mechanically convert back and forth between formulas and Gödel numbers. It is similar, for example, to the way English sentences are encoded as sequences (or "strings") of numbers using ASCII: such a sequence is considered as a single (if potentially very large) number. Because our

system is strong enough to reason about *numbers*, it is now also possible to reason about *formulas* within the system.

A formula $F(x)$ that contains exactly one free variable x is called a *statement form* or *class-sign*. As soon as x is replaced by a specific number, the statement form turns into a *bona fide* statement, and it is then either provable in the system, or not. For certain formulas one can show that for every natural number n, F(n) is true if and only if it can be proven (the precise requirement in the original proof is weaker, but for the proof sketch this will suffice). In particular, this is true for every specific arithmetic operation between a finite number of natural numbers, such as "2×3=6".

Statement forms themselves are not statements and therefore cannot be proved or disproved. But every statement form $F(x)$ can be assigned with a Gödel number which we will denote by $\mathbf{G}(F)$. The choice of the free variable used in the form $F(x)$ is not relevant to the assignment of the Gödel number $\mathbf{G}(F)$.

Now comes the trick: The notion of provability itself can also be encoded by Gödel numbers, in the following way. Since a proof is a list of statements which obey certain rules, we can define the Gödel number of a proof. Now, for every statement p, we may ask whether a number x is the Gödel number of its proof. The relation between the Gödel number of p and x, the Gödel number of its proof, is an arithmetical relation between two numbers. Therefore there is a statement form Bew(x) that uses this arithmetical relation to state that a Gödel number of a proof of x exists:

> Bew(y) = ∃ x (y is the Gödel number of a formula and x is the Gödel number of a proof of the formula encoded by y).

The name **Bew** is short for *beweisbar*, the German word for "provable"; this name was originally used by Gödel to denote the provability formula just described. Note that "Bew(y)" is merely an abbreviation that represents a particular, very long, formula in the original language of T; the string "Bew" itself is not claimed to be part of this language.

An important feature of the formula Bew(y) is that if a statement p is provable in the system then Bew($\mathbf{G}(p)$) is also provable. This is because any proof of p would have a corresponding Gödel number, the existence of which causes Bew($\mathbf{G}(p)$) to be satisfied.

Diagonalization

The next step in the proof is to obtain a statement that says it is unprovable. Although Gödel constructed this statement directly, the existence of at least one such statement follows from the diagonal lemma, which says that for any sufficiently strong formal system and any statement form F there is a statement p such that the system proves

$$p \leftrightarrow F(\mathbf{G}(p)).$$

We obtain p by letting F be the negation of Bew(x); thus p roughly states that its own Gödel number is the Gödel number of an unprovable formula.

The statement p is not literally equal to ~Bew($\mathbf{G}(p)$); rather, p states that if a certain calculation is performed, the resulting Gödel number will be that of an unprovable statement. But when this calculation is performed, the resulting Gödel number turns out to be the Gödel number of p itself. This is similar to the following sentence in English:

> ", when preceded by itself in quotes, is unprovable.", when preceded by itself in quotes, is unprovable.

This sentence does not directly refer to itself, but when the stated transformation is made the original sentence is obtained as a result, and thus this sentence asserts its own unprovability. The proof of the diagonal lemma employs a similar method.

Proof of independence

We will now assume that our axiomatic system is ω-consistent. We let p be the statement obtained in the previous section.

If p were provable, then Bew(**G**(p)) would be provable, as argued above. But p asserts the negation of Bew(**G**(p)). Thus our system would be inconsistent, proving both a statement and its negation. This contradiction shows that p cannot be provable.

If the negation of p were provable, then Bew(**G**(p)) would be provable (because p was constructed to be equivalent to the negation of Bew(**G**(p))). However, for each specific number x, x cannot be the Gödel number of the proof of p, because p is not provable (from the previous paragraph). Thus on one hand the system proves there is a number with a certain property (that it is the Gödel number of the proof of p), but on the other hand, for every specific number x, we can prove that it does not have this property. This is impossible in an ω-consistent system. Thus the negation of p is not provable.

Thus the statement p is undecidable: it can neither be proved nor disproved within the system.

It should be noted that p is not provable (and thus true) in every consistent system. The assumption of ω-consistency is only required for the negation of p to be not provable. Thus:

- In an ω-consistent formal system, we may prove neither p nor its negation, and so p is undecidable.
- In a consistent formal system we may either have the same situation, or we may prove the negation of p; In the later case, we have a statement ("not p") which is false but provable.

Note that if one tries to "add the missing axioms" to avoid the undecidability of the system, then one has to add either p or "not p" as axioms. But then the definition of "being a Gödel number of a proof" of a statement changes. which means that the statement form Bew(x) is now different. Thus when we apply the diagonal lemma to this new form Bew, we obtain a new statement p, different from the previous one, which will be undecidable in the new system if it is ω-consistent.

Proof via Berry's paradox

George Boolos (1989) sketches an alternative proof of the first incompleteness theorem that uses Berry's paradox rather than the liar paradox to construct a true but unprovable formula. A similar proof method was independently discovered by Saul Kripke (Boolos 1998, p. 383). Boolos's proof proceeds by constructing, for any computably enumerable set S of true sentences of arithmetic, another sentence which is true but not contained in S. This gives the first incompleteness theorem as a corollary. According to Boolos, this proof is interesting because it provides a "different sort of reason" for the incompleteness of effective, consistent theories of arithmetic (Boolos 1998, p. 388).

Formalized proofs

Formalized proofs of versions of the incompleteness theorem have been developed by N. Shankar in 1986 using Nqthm (Shankar 1994) and by R. O'Connor in 2003 using Coq (O'Connor 2005).

Proof sketch for the second theorem

The main difficulty in proving the second incompleteness theorem is to show that various facts about provability used in the proof of the first incompleteness theorem can be formalized within the system using a formal predicate for provability. Once this is done, the second incompleteness theorem essentially follows by formalizing the entire proof of the first incompleteness theorem within the system itself.

Let p stand for the undecidable sentence constructed above, and assume that the consistency of the system can be proven from within the system itself. We have seen above that if the system is consistent, then p is not provable. The proof of this implication can be formalized within the system, and therefore the statement "p is not provable", or "not

$P(p)$" can be proven in the system.

But this last statement is equivalent to p itself (and this equivalence can be proven in the system), so p can be proven in the system. This contradiction shows that the system must be inconsistent.

Discussion and implications

The incompleteness results affect the philosophy of mathematics, particularly versions of formalism, which use a single system formal logic to define their principles. One can paraphrase the first theorem as saying the following:

> We can never find an all-encompassing axiomatic system which is able to prove *all* mathematical truths, but no falsehoods.

On the other hand, from a strict formalist perspective this paraphrase would be considered meaningless because it presupposes that mathematical "truth" and "falsehood" are well-defined in an absolute sense, rather than relative to each formal system.

The following rephrasing of the second theorem is even more unsettling to the foundations of mathematics:

> If an axiomatic system can be proven to be consistent **and complete** from within itself, then it is inconsistent.

Therefore, to establish the consistency of a system S, one needs to use some other *more powerful* system T, but a proof in T is not completely convincing unless T's consistency has already been established without using S.

At first, Gödel's theorems seemed to leave some hope—it was thought that it might be possible to produce a general algorithm that indicates whether a given statement is undecidable or not, thus allowing mathematicians to bypass the undecidable statements altogether. However, the negative answer to the Entscheidungsproblem, obtained in 1936, showed that no such algorithm exists.

There are some who hold that a statement that is unprovable within a deductive system may be quite provable in a metalanguage. And what cannot be proven in *that* metalanguage can likely be proven in a **meta**-metalanguage, recursively, ad infinitum, in principle. By invoking such a system of typed metalanguages, along with an axiom of Reducibility — which by an inductive assumption applies to the entire stack of languages — one may, for all practical purposes, overcome the obstacle of incompleteness.

Note that Gödel's theorems only apply to *sufficiently strong* axiomatic systems. "Sufficiently strong" means that the theory contains enough arithmetic to carry out the coding constructions needed for the proof of the first incompleteness theorem. Essentially, all that is required are some basic facts about addition and multiplication as formalized, for example, in Robinson arithmetic Q. There are even weaker axiomatic systems that are consistent and complete, for instance Presburger arithmetic which proves every true first-order statement involving only addition.

The axiomatic system may consist of infinitely many axioms (as first-order Peano arithmetic does), but for Gödel's theorem to apply, there has to be an effective algorithm which is able to check proofs for correctness. For instance, one might take the set of all first-order sentences which are true in the standard model of the natural numbers. This system is complete; Gödel's theorem does not apply because there is no effective procedure that decides if a given sentence is an axiom. In fact, that this is so is a consequence of Gödel's first incompleteness theorem.

Another example of a specification of a theory to which Gödel's first theorem does not apply can be constructed as follows: order all possible statements about natural numbers first by length and then lexicographically, start with an axiomatic system initially equal to the Peano axioms, go through your list of statements one by one, and, if the current statement cannot be proven nor disproven from the current axiom system, add it to that system. This creates a system which is complete, consistent, and sufficiently powerful, but not computably enumerable.

Gödel himself only proved a technically slightly weaker version of the above theorems; the first proof for the versions stated above was given by J. Barkley Rosser in 1936.

In essence, the proof of the first theorem consists of constructing a statement p within a formal axiomatic system that can be given a meta-mathematical interpretation of:

p = "This statement cannot be proven in the given formal theory"

As such, it can be seen as a modern variant of the Liar paradox, although unlike the classical paradoxes it is not really paradoxical.

If the axiomatic system is consistent, Gödel's proof shows that p (and its negation) cannot be proven in the system. Therefore p is true (p claims to be not provable, and it is not provable) yet it cannot be formally proved in the system. If the axiomatic system is ω-consistent, then the negation of p cannot be proven either, and so p is undecidable. In a system which is not ω-consistent (but consistent), either we have the same situation, or we have a false statement which can be proven (namely, the negation of p).

Adding p to the axioms of the system would not solve the problem: there would be another Gödel sentence for the enlarged theory. Theories such as Peano arithmetic, for which any computably enumerable consistent extension is incomplete, are called **essentially incomplete**.

Minds and machines

Authors including J. R. Lucas have debated what, if anything, Gödel's incompleteness theorems imply about human intelligence. Much of the debate centers on whether the human mind is equivalent to a Turing machine, or by the Church–Turing thesis, any finite machine at all. If it is, and if the machine is consistent, then Gödel's incompleteness theorems would apply to it.

Hilary Putnam (1960) suggested that while Gödel's theorems cannot be applied to humans, since they make mistakes and are therefore inconsistent, it may be applied to the human faculty of science or mathematics in general. If we are to assume that it is consistent, then either we cannot prove its consistency, or it cannot be represented by a Turing machine.

Appeals to the incompleteness theorems in other fields

Appeals and analogies are sometimes made to the incompleteness theorems in support of arguments that go beyond mathematics and logic. A number of authors have commented negatively on such extensions and interpretations, including Torkel Franzén (2005); Alan Sokal and Jean Bricmont (1999); and Ophelia Benson and Jeremy Stangroom (2006). Bricmont and Stangroom (2006, p. 10), for example, quote from Rebecca Goldstein's comments on the disparity between Gödel's avowed Platonism and the anti-realist uses to which his ideas are sometimes put. Sokal and Bricmont (1999, p. 187) criticize Régis Debray's invocation of the theorem in the context of sociology; Debray has defended this use as metaphorical (ibid.). Carl Hewitt (2008, 2009) has shown that Gödel's result can be extended to prove incompleteness theorems in certain non-classical, paraconsistent logics with proposed applications in software engineering.

See also

- Gödel's completeness theorem
- Löb's Theorem
- Provability logic
- Münchhausen Trilemma
- Non-standard model of arithmetic
- Tarski's indefinability theorem
- *Minds, Machines and Gödel*
- Third Man Argument

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Translations, during his lifetime, of Gödel's paper into English

None of the following agree in all translated words and in typography. The typography is a serious matter, because Gödel expressly wished to emphasize "those metamathematical notions that had been defined in their usual sense before . . ."(van Heijenoort 1967:595). Three translations exist. Of the first John Dawson states that: "The Meltzer translation was seriously deficient and received a devastating review in the *Journal of Symbolic Logic*; "Gödel also complained about Braithwaite's commentary (Dawson 1997:216). "Fortunately, the Meltzer translation was soon supplanted by a better one prepared by Elliott Mendelson for Martin Davis's anthology *The Undecidable* . . . he found the translation "not quite so good" as he had expected . . . [but because of time constraints he] agreed to its publication" (ibid). (In a footnote Dawson states that "he would regret his compliance, for the published volume was marred throughout by sloppy typography and numerous misprints" (ibid)). Dawson states that "The translation that Gödel favored was that by Jean van Heijenoort"(ibid). For the serious student another version exists as a set of lecture notes recorded by Stephen Kleene and J. B. Rosser "during lectures given by Gödel at to the Institute for Advanced Study during the spring of 1934" (cf commentary by Davis 1965:39 and beginning on p. 41); this version is titled "On Undecidable Propositions of Formal Mathematical Systems". In their order of publication:

- B. Meltzer (translation) and R. B. Braithwaite (Introduction), 1962. *On Formally Undecidable Propositions of Principia Mathematica and Related Systems*, Dover Publications, New York (Dover edition 1992), ISBN 0-486-66980-7 (pbk.) This contains a useful translation of Gödel's German abbreviations on pp. 33–34. As noted above, typography, translation and commentary is suspect. Unfortunately, this translation was reprinted with all its suspect content by
  - Stephen Hawking editor, 2005. *God Created the Integers: The Mathematical Breakthroughs That Changed History*, Running Press, Philadelphia, ISBN 0-7624-1922-9. Gödel's paper appears starting on p. 1097, with Hawking's commentary starting on p. 1089.
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- Jean van Heijenoort editor, 1967, 3rd edition 1967. *From Frege to Gödel: A Source Book in Mathematical Logic, 1979-1931*, Harvard University Press, Cambridge Mass., ISBN 0-674-32449-8 (pbk). van Heijenoort did the translation. He states that "Professor Gödel approved the translation, which in many places was accommodated to his wishes."(p. 595). Gödel's paper begins on p. 595; van Heijenoort's commentary begins on p. 592.
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External links

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- MacTutor biographies:
  - Kurt Gödel. [16]
  - Gerhard Gentzen. [17]
  - What is Mathematics:Gödel's Theorem and Around [18] by *Karlis Podnieks*. An online free book.
- World's shortest explanation of Gödel's theorem [19] using a printing machine as an example.

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[1] The word "true" is used disquotationally here: the Gödel sentence is true in this sense because it "asserts its own unprovability and it is indeed unprovable" (Smoryński 1977 p. 825; also see Franzén 2005 pp. 28–33). It is also possible to read "G_T is true" in the formal sense that primitive recursive arithmetic proves the implication Con(T)$\rightarrow G_T$, where Con(T) is a canonical sentence asserting the consistency of T (Smoryński 1977 p. 840, Kikuchi and Tanaka 1994 p. 403)

[2] For example, the conjunction of the Gödel sentence and any logically valid sentence will have this property.

[3] http://www.research.ibm.com/people/h/hirzel/papers/canon00-goedel.pdf

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[19] http://blog.plover.com/math/Gdl-Smullyan.html

Tarski's undefinability theorem

Tarski's undefinability theorem, stated and proved by Alfred Tarski in 1936, is an important limitative result in mathematical logic, the foundations of mathematics, and in formal semantics. Informally, the theorem states that *arithmetical truth cannot be defined in arithmetic*.

The theorem applies more generally to any sufficiently strong formal system, showing that truth in the standard model of the system cannot be defined within the system.

History

In 1931, Kurt Gödel published his famous incompleteness theorems, which he proved in part by showing how to represent *syntax* within (first-order) arithmetic. Each expression of the language of arithmetic is assigned a distinct number. This procedure is known variously as Gödel-numbering, *coding*, and more generally, as arithmetization.

In particular, various *sets* of expressions are coded as sets of numbers. It turns out that for various syntactic properties (such as *being a formula*, *being a sentence*, etc.), these sets are computable. Moreover, any computable set of numbers can be defined by some arithmetical formula. For example, there are formulas in the language of arithmetic defining the set of codes for arithmetic sentences, and for provable arithmetic sentences.

The indefinability theorem shows that this encoding cannot be done for semantical concepts such as truth. It shows that no sufficiently rich interpreted language can represent its own semantics. A corollary is that any metalanguage capable of expressing the semantics of some object language must have expressive power exceeding that of the object language. The metalanguage includes primitive notions, axioms, and rules absent from the object language, so that there are theorems provable in the metalanguage not provable in the object language.

The indefinability theorem is conventionally attributed to Alfred Tarski. Gödel also discovered the indefinability theorem in 1930, while proving his incompleteness theorems published in 1931, and well before the 1936

publication of Tarski's work (Murawski 1998). While Gödel never published anything bearing on his independent discovery of indefinability, he did describe it in a 1931 letter to John von Neumann. Tarski had obtained almost all results of his 1936 paper *Der Wahrheitsbegriff in den formalisierten Sprachen* between 1929 and 1931, and spoke about them to Polish audiences. However, as he emphasized in the paper, the indefinability theorem was the only one exception. According to the footnote of the indefinability theorem (Satz I) of the 1936 paper, the theorem and the sketch of the proof were added to the paper only after the paper was sent to print. When he presented the paper to the Warsaw Academy of Science on March 21 1931, he wrote only some conjectures instead of the results after his own investigations and partly after Gödel's short report on the incompleteness theorems "Einige metamathematische Resultate über Entscheidungsdefinitheit und Widerspruchsfreiheit", Akd. der Wiss. in Wien, 1930.

Statement of the theorem

We will first state a simplified version of Tarski's theorem, then state and prove in the next section the theorem Tarski actually proved in 1936. Let *L* be the language of first-order arithmetic, and let *N* be the standard structure for *L*. Thus (*L*, *N*) is the "interpreted first-order language of arithmetic." Let *T* denote the set of *L*-sentences true in *N*, and *T** the set of code numbers of the sentences in *T*. The following theorem answers the question: Can *T** be defined by a formula of first-order arithmetic?

Tarski's undefinability theorem: There is no *L*-formula *True*(*x*) which defines *T**. That is, there is no *L*-formula *True*(*x*) such that for every *L*-formula *x*, *True*(*x*) ↔ *x* is true.

Informally, the theorem says that given some formal arithmetic, the concept of truth in that arithmetic is not definable using the expressive means that arithmetic affords. This implies a major limitation on the scope of "self-representation." It *is* possible to define a formula *True*(*x*) whose extension is *T**, but only by drawing on a metalanguage whose expressive power goes beyond that of *L*, second-order arithmetic for example.

The theorem just stated is a corollary of Post's theorem about the arithmetical hierarchy, proved some years after Tarski (1936). A semantic proof of Tarski's theorem from Post's theorem is obtained by reductio ad absurdum as follows. Assuming *T** is arithmetically definable, there is a natural number *n* such that *T** is definable by a formula at level Σ^0_n of the arithmetical hierarchy. However, *T** is Σ^0_k complete for all *k*. Thus the arithmetical hierarchy collapses at level *n*, contradicting Post's theorem.

General form of the theorem

Tarski proved a stronger theorem than the one stated above, using an entirely syntactical method. The resulting theorem applies to any formal language with negation, and with sufficient capability for self-reference that Gödel's Diagonal Lemma holds. First-order arithmetic satisfies these preconditions, but the theorem applies to much more general formal systems.

Proof of Tarski's undefinability theorem in its most general form, by reductio ad absurdum. Suppose that an *L*-formula *True*(*x*) defines *T**. In particular, if *A* is a sentence of arithmetic then *True*(*"A"*) is true in *N* iff *A* is true in *N*. Hence for all *A*, the Tarski *T*-sentence *True*(*"A"*) ↔ *A* is true in *N*. But Gödel's diagonal lemma yields a counterexample to this equivalence: the "Liar" sentence *S* such that *S* ↔ ¬*True*(*"S"*) holds. Thus no *L*-formula *True*(*x*) can define *T**. QED.

The formal machinery of this proof is wholly elementary except for the diagonalization the diagonal lemma requires. The proof of that Lemma is likewise surprisingly simple; for example, it does not invoke recursive functions in any way. The proof does assume that every *L*-formula has a Gödel number, but the specifics of a coding method are not required. Hence Tarski's theorem is much easier to motivate and prove than the more celebrated theorems of Gödel about the metamathematical properties of first-order arithmetic.

Discussion

Smullyan (1991, 2001) has argued forcefully that Tarski's undefinability theorem deserves much of the attention garnered by Gödel's incompleteness theorems. That the latter theorems have much to say about all of mathematics and more controversially, about a range of philosophical issues (e.g., Lucas 1961) is less than evident. Tarski's theorem, on the other hand, is not directly about mathematics but about the inherent limitations of any formal language sufficiently expressive to be of real interest. Such languages are necessarily capable of enough self-reference for the diagonal lemma to apply to them. The broader philosophical import of Tarski's theorem is more strikingly evident.

An interpreted language is *strongly-semantically-self-representational* exactly when the language contains predicates and function symbols defining all the semantic concepts specific to the language. Hence the required functions include the "semantic valuation function" mapping a formula A to its truth value $\|A\|$, and the "semantic denotation function" mapping a term t to the object it denotes. Tarski's theorem then generalizes as follows: *No sufficiently powerful language is strongly-semantically-self-representational*.

The undefinability theorem does not prevent truth in one theory from being defined in a stronger theory. For example, the set of (codes for) formulas of first-order Peano arithmetic that are true in N is definable by a formula in second order arithmetic. Similarly, the set of true formulas of the standard model of second order arithmetic (or n-th order arithmetic for any n) can be defined by a formula in first-order ZFC.

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Model of hierarchical complexity

The **model of hierarchical complexity,** is a framework for scoring how complex a behavior is. It quantifies the order of hierarchical complexity of a task based on mathematical principles of how the information is organized and of information science. This model has been developed by Michael Commons and others since the 1980s.

Overview

The Model of Hierarchical Complexity, which has been presented as a formal theory [1] , is a framework for scoring how complex a behavior is. Developed by Michael Commons[2] , it quantifies the order of hierarchical complexity of a task based on mathematical principles of how the information is organized [3] , and of information science [4] . Its forerunner was the General Stage Model [5] . It is a model in mathematical psychology.

Behaviors that may be scored include those of individual humans or their social groupings (e.g., organizations, governments, societies), animals, or machines. It enables scoring the complexity of human reasoning in any domain. It is cross-culturally valid. The reason it applies cross-culturally is that the scoring is based on the mathematical complexity of the hierarchical organization of information. Scoring does not depend upon the content of the information (e.g., what is done, said, written, or analyzed) but upon how the information is organized.

The MHC is a non-mentalistic model of developmental stages. It specifies 14 orders of hierarchical complexity and their corresponding stages. It is different from previous proposals about developmental stage applied to humans [6] . Instead of attributing behavioral changes across a person's age to the development of mental structures or schema, this model posits that task sequences form hierarchies that become increasingly complex. Because less complex tasks must be completed and practiced before more complex tasks can be acquired, this accounts for the developmental changes seen, for example, in individual persons' performance of tasks. (For example, a person cannot perform arithmetic until the numeral representations of numbers are learned. A person cannot multiply numbers until addition is learned). Furthermore, previous theories of stage have confounded the stimulus and response in assessing stage by simply scoring responses and ignoring the task or stimulus. The Model of Hierarchical Complexity separates the task or stimulus from the performance. The participant's performance on a task of a given complexity represents the stage of developmental complexity.

Vertical complexity of tasks performed

One major basis for this developmental theory is task analysis. The study of ideal tasks, including their instantiation in the real world, has been the basis of the branch of stimulus control called psychophysics. Tasks are defined as sequences of contingencies, each presenting stimuli and each requiring a behavior or a sequence of behaviors that must occur in some non-arbitrary fashion. The complexity of behaviors necessary to complete a task can be specified using the horizontal complexity and vertical complexity definitions described below. Behavior is examined with respect to the analytically-known complexity of the task.

Tasks are quantal in nature. They are either completed correctly or not completed at all. There is no intermediate state. For this reason, the Model characterizes all stages as hard and distinct. The orders of hierarchical complexity are quantized like the electron atomic orbitals around the nucleus. Each task difficulty has an order of hierarchical complexity required to complete it correctly. Since tasks of a given order of hierarchical complexity require actions of a given order of hierarchical complexity to perform them, the stage of the participant's performance is equivalent to the order of complexity of the successfully completed task. The quantal feature of tasks is thus particularly instrumental in stage assessment because the scores obtained for stages are likewise discrete.

Every task contains a multitude of subtasks (Overton, 1990). When the subtasks are carried out by the participant in a required order, the task in question is successfully completed. Therefore, the model asserts that all tasks fit in some sequence of tasks, making it possible to precisely determine the hierarchical order of task complexity. Tasks vary in

complexity in two ways: either as *horizontal* (involving classical information); or as *vertical* (involving hierarchical information).

Horizontal complexity

Classical information describes the number of “yes-no” questions it takes to do a task. For example, if one asked a person across the room whether a penny came up heads when they flipped it, their saying “heads” would transmit 1 bit of “horizontal” information. If there were 2 pennies, one would have to ask at least two questions, one about each penny. Hence, each additional 1-bit question would add another bit. Let us say they had a four-faced top with the faces numbered 1, 2, 3, and 4. Instead of spinning it, they tossed it against a backboard as one does with dice in a game of craps. Again, there would be 2 bits. One could ask them whether the face had an even number. If it did, one would then ask if it were a 2. Horizontal complexity, then, is the sum of bits required by just such tasks as these.

Vertical complexity

Hierarchical complexity refers to the number of recursions that the coordinating actions must perform on a set of primary elements. Actions at a higher order of hierarchical complexity: (a) are defined in terms of actions at the next lower order of hierarchical complexity; (b) organize and transform the lower-order actions (see Figure 2); (c) produce organizations of lower-order actions that are new and not arbitrary, and cannot be accomplished by those lower-order actions alone. Once these conditions have been met, we say the higher-order action coordinates the actions of the next lower order.

To illustrate how lower actions get organized into more hierarchically complex actions, let us turn to a simple example. Completing the entire operation 3 x (4 + 1) constitutes a task requiring the distributive act. That act non-arbitrarily orders adding and multiplying to coordinate them. The distributive act is therefore one order more hierarchically complex than the acts of adding and multiplying alone; it indicates the singular proper sequence of the simpler actions. Although simply adding results in the same answer, people who can do both display a greater freedom of mental functioning. Thus, the order of complexity of the task is determined through analyzing the demands of each task by breaking it down into its constituent parts.

The hierarchical complexity of a task refers to the number of concatenation operations it contains, that is, the number of recursions that the coordinating actions must perform. An order-three task has three concatenation operations. A task of order three operates on a task of order two and a task of order two operates on a task of order one (a simple task).

Stages of development

The notion of stages is fundamental in the description of human, organismic, and [7] machine evolution. Previously it has been defined in some ad hoc ways. Here, it is described formally in terms of the Model of Hierarchical Complexity (MHC).

Formal definition of stage

Since actions are defined inductively, so is the function *h*, known as the order of the hierarchical complexity. To each action *A*, we wish to associate a notion of that action's hierarchical complexity, *h(A)*. Given a collection of actions **A** and a participant *S* performing **A**, the *stage of performance* of *S* on **A** is the highest order of the actions in **A** completed successfully at least once, i.e., it is stage (*S*, **A**) = max{*h(A)* | *A* (epsilon) **A** and *A* completed successfully by *S*}. Thus, the notion of stage is discontinuous, having the same gaps as the orders of hierarchical complexity. This is in agreement with previous definitions (Commons et al., 1998; Commons & Miller, 2001; Commons & Pekker, 2007).

Because MHC stages are conceptualized in terms of the hierarchical complexity of tasks rather than in terms of mental representations (as in Piaget's stages), the highest stage represents successful performances on the most hierarchically complex tasks rather than intellectual maturity. Table 1 gives descriptions of each stage.

Stages of hierarchical complexity

Table 1. Stages described in the Model of Hierarchical Complexity

Order or Stage	What they do	How they do it	End result
0 - calculatory	Exact computation only, no generalization	Human-made programs manipulate 0, 1, not 2 or 3.	Minimal human result. Literal, unreasoning computer programs act in a way analogous to this stage.
1 - sensory or motor	Discriminate in a rote fashion, stimuli generalization, move	Move limbs, lips, toes, eyes, elbows, head View objects or move	Discriminative establishing and conditioned reinforcing stimuli
2 - circular sensory-motor	Form open-ended proper classes	Reach, touch, grab, shake objects, circular babble	Open ended proper classes, phonemes, archiphonemes
3 - sensory-motor	Form concepts	Respond to stimuli in a class successfully	Morphemes, concepts
4 - nominal	Find relations among concepts. Use names	Find relations among concepts Use names	Single words: ejaculatives & exclamations, verbs, nouns, number names, letter names
5 - sentential	Imitate and acquire sequences Follows short sequential acts	Generalize match-dependent task actions. Chain words	Various forms of pronouns: subject (I), object (me), possessive adjective (my), possessive pronoun (mine), and reflexive (myself) for various persons (I, you, he, she, it, we, y'all, they)
6 - preoperational	Make simple deductions. Follow lists of sequential acts. Tell stories.	Count event events and objects Connect the dots Combine numbers and simple propositions	Connectives: as, when, then, why, before; products of simple operations
7 - primary	Simple logical deduction and empirical rules involving time sequence Simple arithmetic	Adds, subtracts, multiplies, divides, counts, proves, does series of tasks on own	Times, places, counts acts, actors, arithmetic outcome, sequence from calculation
8 - concrete	Carry out full arithmetic, form cliques, plan deals	Does long division, short division, follows complex social rules, ignores simple social rules, takes and coordinates perspective of other and self	Interrelations, social events, what happened among others, reasonable deals, history, geography
9 - abstract	Discriminate variables such as stereotypes; logical quantification; (none, some, all)	Form variables out of finite classes Make and quantify propositions	Variable time, place, act, actor, state, type; quantifiers (all, none, some); categorical assertions (e.g., "We all die")
10 - formal	Argue using empirical or logical evidence Logic is linear, 1 dimensional	Solve problems with one unknown using algebra, logic and empiricism	Relationships (for example: causality) are formed out of variables; words: linear, logical, one dimensional, if then, thus, therefore, because; correct scientific solutions
11- systematic	Construct multivariate systems and matrices	Coordinates more than one variable as input. Consider relationships in contexts.	Events and concepts situated in a multivariate context; systems are formed out of relations; systems: legal, societal, corporate, economic, national

12 - metasystematic	Construct multi-systems and metasystems out of disparate systems	Create metasystems out of systems Compare systems and perspectives Name properties of systems: e.g. homomorphic, isomorphic, complete, consistent (such as tested by consistency proofs), commensurable	Metasystems and supersystems are formed out of systems of relationships
13 - paradigmatic	Fit metasystems together to form new paradigms	Synthesize metasystems	Paradigms are formed out of multiple metasystems
14 - cross-paradigmatic	Fit paradigms together to form new fields	Form new fields by crossing paradigms	New fields are formed out of multiple paradigms

Relationship with Piaget's theory

There are some commonalities between the Piagetian and Commons' notions of stage and many more things that are different. In both, one finds:

1. Higher order actions defined in terms of lower order actions. This forces the hierarchical nature of the relations and makes the higher order tasks include the lower ones and requires that lower order actions are hierarchically contained within the relative definitions of the higher order tasks.

2. Higher order of complexity actions organize those lower order actions. This makes them more powerful. Lower order actions are organized by the actions with a higher order of complexity, i.e., the more complex tasks.

What Commons et al. (1998) have added includes:

3. Higher order of complexity actions organize those lower order actions in a non-arbitrary way.

This makes it possible for the Model's application to meet real world requirements, including the empirical and analytic. Arbitrary organization of lower order of complexity actions, possible in the Piagetian theory, despite the hierarchical definition structure, leaves the functional correlates of the interrelationships of tasks of differential complexity formulations ill-defined.

Moreover, the model is consistent with the neo-Piagetian theories of cognitive development. According to these theories, progression to higher stages or levels of cognitive development is caused by increases in processing efficiency and working memory capacity. That is, higher order stages place increasingly higher demands on these functions of information processing, so that their order of appearance reflects the information processing possibilities at successive ages (Demetriou, 1998).

The following dimensions are inherent in the application:

1. Task and performance are separated
2. All tasks have an order of hierarchical complexity
3. There is only one sequence of orders of hierarchical complexity.
4. Hence, there is structure of the whole for ideal tasks and actions
5. There are gaps between the orders of hierarchical complexity
6. Stage is defined as the most hierarchically complex task solved.
7. There are gaps in Rasch Scaled Stage of Performance.
8. Performance stage is different task area to task area.
9. There is no structure of the whole—horizontal decaláge—for performance. It is not inconsistency in thinking within a developmental stage. Decaláge is the normal modal state of affairs.

Orders and corresponding stages

The MHC specifies 15 orders of hierarchical complexity and their corresponding stages, showing that each of Piaget's substages, in fact, are hard stages. Commons also adds four postformal stages: Systematic stage 11, Metasystematic stage 12, Paradigmatic stage 13, and Crossparadigmatic stage 14. It may be the Piaget's consolidate formal stage is the same as the systematic stage. There is one other difference in the orders and stages. At the suggestion of Biggs and Biggs, the sentential stage 5 was added. The sequence is as follows: (0) computory, (1) sensory & motor, (2) circular sensory-motor, (3) sensory-motor, (4) nominal, the new (5) sentential, (6) preoperational, (7) primary, (8) concrete, (9) abstract, (10) formal, and the four postformal: (11) systematic, (12) metasystematic, (13) paradigmatic, and (14) cross-paradigmatic. The first four stages (0-3) correspond to Piaget's sensorimotor stage at which infants and very young children perform. The sentential stage was added at Fischer's suggestion (1981, personal communication) citing Biggs & Collis (1982). Adolescents and adults can perform at any of the subsequent stages. MHC stages 4 through 5 correspond to Piaget's pre-operational stage; 6 through 8 correspond to his concrete operational stage; and 9 through 11 correspond to his formal operational stage.

The three highest stages in the MHC are not represented in Piaget's model. These stages from the Model of Hierarchical Complexity have extensively influenced the field of Positive Adult Development. Few individuals perform at stages above formal operations. More complex behaviors characterize multiple system models (Kallio, 1995; Kallio & Helkama, 1991). Some adults are said to develop alternatives to, and perspectives on, formal operations. They use formal operations within a "higher" system of operations and transcend the limitations of formal operations. In any case, these are all ways in which these theories argue for and present converging evidence that adults are using forms of reasoning that are more complex than formal operations with which Piaget's model ended.

Empirical research using the model

The MHC has a broad range of applicability. The mathematical foundation of the model makes it an excellent research tool to be used by anyone examining performance that is organized into stages. It is designed to assess development based on the order of complexity which the individual utilizes to organize information. The MHC offers a singular mathematical method of measuring stages in any domain because the tasks presented can contain any kind of information. The model thus allows for a standard quantitative analysis of developmental complexity in any cultural setting. Other advantages of this model include its avoidance of mentalistic or contextual explanations, as well as its use of purely quantitative principles which are universally applicable in any context.

The following can use the Model of Hierarchical Complexity to quantitatively assess developmental stages:

- Cross-cultural developmentalists;
- Animal developmentalists;
- Evolutionary psychologists;
- Organizational psychologists;
- Developmental political psychologists;
- Learning theorists;
- Perception researchers;
- History of science historians;
- Educators;
- Therapists;
- Anthropologists.

The following list shows the large range of domains to which the Model has been applied. In one representative study, Commons, Goodheart, and Dawson (1997) found, using Rasch (1980) analysis, that hierarchical complexity of a given task predicts stage of a performance, the correlation being r = .92. Correlations of similar magnitude have been found in a number of the studies.

List of examples

List of examples of tasks studied using the Model of Hierarchical Complexity or *Fischer's Skill Theory* (1980):

- Algebra (Commons, in preparation)
- Animal stages (Commons & Miller, 2004)
- Atheism (Commons-Miller, 2005)
- Attachment and Loss (Commons, 1991; Miller & Lee, 2000)
- Balance beam and pendulum (Commons, Goodheart, & Bresette, 1995; Commons, Pekker, et al., 2007)
- Contingencies of reinforcement (Commons, in preparation)
- Counselor stages (Lovell, 2004)
- Empathy of Hominids (Commons & Wolfsont, 2002)
- Epistemology (Kitchener & King, 1990; Kitchener & Fischer, 1990)
- Evaluative reasoning (Dawson, 2000)
- Four Story problem (Commons, Richards & Kuhn, 1982; Kallio & Helkama, 1991)
- Good Education (Dawson-Tunik, 2004)
- Good Interpersonal (Armon, 1989)
- Good Work (Armon, 1993)
- Honesty and Kindness (Lamborn, Fischer & Pipp, 1994)
- Informed consent (Commons & Rodriguez, 1990, 1993; Commons, Goodheart, Rodriguez, & Gutheil, 2006; Commons, Rodriguez, Adams, Goodheart, Gutheil, & Cyr, 2007).
- Language stages (Commons, et al., 2007)
- Leadership before and after crises (Oliver, 2004)
- Loevinger's Sentence Completion task (Cook-Greuter, 1990)
- Moral Judgment, (Armon & Dawson, 1997; Dawson, 2000)
- Music (Beethoven) (Funk, 1989)
- Orienteering (Commons, in preparation)
- Physics tasks (Inhelder & Piaget, 1958)
- Political development (Sonnert & Commons, 1994)
- Relationships (Armon, 1984a, 1984b)
- Report patient's prior crimes (Commons, Lee, Gutheil, et al., 1995)
- Social perspective-taking (Commons & Rodriguez, 1990; 1993)
- Spirituality (Miller & Cook-Greuter, 2000)
- Tool Making of Hominids (Commons & Miller 2002)
- Views of the Agood life@ (Armon, 1984c; Danaher, 1993; Dawson, 2000; Lam, 1995)
- Workplace culture (Commons, Krause, Fayer, & Meaney, 1993)
- Workplace organization (Bowman, 1996a, 1996b)
- Writing (Commons & DeVos, 1985)

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[2] (Commons, Trudeau, Stein, Richards, & Krause, 1998)
[3] (Coombs, Dawes, & Tversky, 1970)
[4] (Commons & Richards, 1984a, 1984b; Lindsay & Norman, 1977; Commons & Rodriguez, 1990, 1993)
[5] (Commons & Richards, 1984a, 1984b)
[6] (e.g., Inhelder & Piaget, 1958)
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External links

- Dare Association, Inc. (http://dareassociation.org) display text.
- Behavioral Development Bulletin (http://www.behavioraldevelopmentbulletin.com) display text.
- Society for Research in Adult Development (http://adultdevelopment.org) display text

Complexity theory

Complexity theory may refer to:

- The study of complex systems.
- Computational complexity theory, a field in theoretical computer science and mathematics dealing with the resources required during computation to solve a given problem.
- The theoretical treatment of Kolmogorov complexity of a string studied in algorithmic information theory by identifying the length of the shortest binary program which can output that string.
- Complexity theory and organizations or complexity theory and strategy, which have been influential in strategic management and organizational studies and incorporate the study of complex adaptive systems.
- Complexity economics, the application of complexity theory to economics.

See also

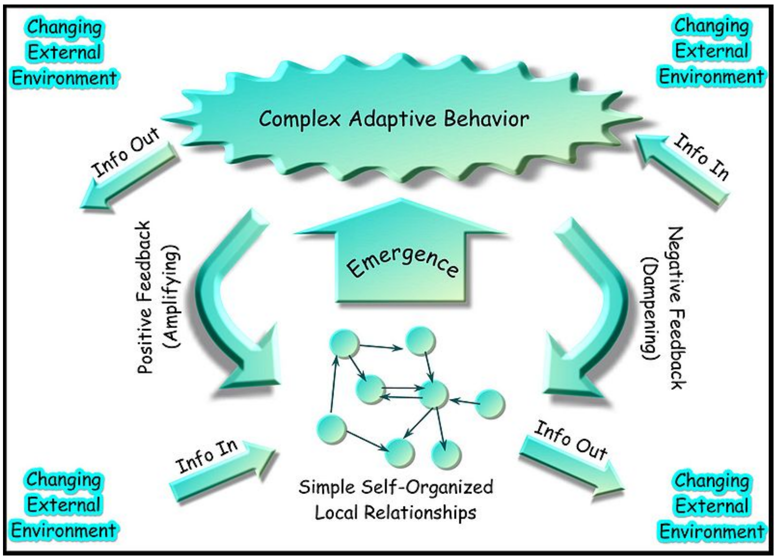
- Systems theory (or *systemics* or *general systems theory*), an interdisciplinary field including engineering, biology, and philosophy that incorporates science to study large systems
- Complexity

Complex adaptive system

Complex adaptive systems are special cases of complex systems. They are *complex* in that they are diverse and made up of multiple interconnected elements (and so a part of network science) and *adaptive* in that they have the capacity to change and learn from experience. The term *complex adaptive systems* (CAS) was coined at the interdisciplinary Santa Fe Institute (SFI), by John H. Holland, Murray Gell-Mann and others.

Overview

The term *complex adaptive systems*, or *complexity science*, is often used to describe the loosely organized academic field that has grown up around the study of such systems. Complexity science is not a single theory— it encompasses more than one theoretical framework and is highly interdisciplinary, seeking the answers to some fundamental questions about living, adaptable, changeable systems.



Complex Adaptive System

Examples of complex adaptive systems include the stock market, social insect and ant colonies, the biosphere and the ecosystem, the brain and the immune system, the cell and the developing embryo, manufacturing businesses and any human social group-based endeavour in a cultural and social system such as political parties or communities. There are close relationships between the field of CAS and artificial life. In both areas the principles of emergence and self-organization are very important.

The ideas and models of CAS are essentially evolutionary, grounded in modern biological views on adaptation and evolution. The theory of complex adaptive systems bridges developments of systems theory with the ideas of generalized Darwinism, which suggests that Darwinian principles of evolution can explain a range of complex material phenomena, from cosmic to social objects.

Definitions

A CAS is a complex, self-similar collection of interacting adaptive agents. The study of CAS focuses on complex, emergent and macroscopic properties of the system. Various definitions have been offered by different researchers:

- John H. Holland

> A Complex Adaptive System (CAS) is a dynamic network of many agents (which may represent cells, species, individuals, firms, nations) acting in parallel, constantly acting and reacting to what the other agents are doing. The control of a CAS tends to be highly dispersed and decentralized. If there is to be any coherent behavior in the system, it has to arise from competition and cooperation among the agents themselves. The overall behavior of the system is the result of a huge number of decisions made every moment by many individual agents.[1]
>
> A CAS behaves/evolves according to three key principles: order is emergent as opposed to predetermined (c.f. Neural Networks), the system's history is irreversible, and the system's future is often unpredictable. The basic

building blocks of the CAS are agents. Agents scan their environment and develop schema representing interpretive and action rules. These schema are subject to change and evolution.[2]

- Other definitions

  Macroscopic collections of simple (and typically nonlinear) interacting units that are endowed with the ability to evolve and adapt to a changing environment.[3]

General properties

What distinguishes a CAS from a pure multi-agent system (MAS) is the focus on top-level properties and features like self-similarity, complexity, emergence and self-organization. A MAS is simply defined as a system composed of multiple, interacting agents. In CASs, the agents as well as the system are adaptive: the system is self-similar. A CAS is a complex, self-similar collectivity of interacting adaptive agents. Complex Adaptive Systems are characterised by a high degree of adaptive capacity, giving them resilience in the face of perturbation.

Other important properties are adaptation (or homeostasis), communication, cooperation, specialization, spatial and temporal organization, and of course reproduction. They can be found on all levels: cells specialize, adapt and reproduce themselves just like larger organisms do. Communication and cooperation take place on all levels, from the agent to the system level. The forces driving co-operation between agents in such a system can be analysed with game theory. Many of the issues of complexity science and new tools for the analysis of complexity are being developed within network science.

Properties

Complex adaptive systems have many properties[4] and the most important are:

- **Emergence**: Rather than being planned or controlled the agents in the system interact in apparently random ways. From all these interactions patterns emerge which informs the behaviour of the agents within the system and the behaviour of the system itself. For example a termite hill is a wondrous piece of architecture with a maze of interconnecting passages, large caverns, ventilation tunnels and much more. Yet there is no grand plan, the hill just emerges as a result of the termites following a few simple local rules.
- **Co-evolution**: All systems exist within their own environment and they are also part of that environment. Therefore, as their environment changes they need to change to ensure best fit. But because they are part of their environment, when they change, they change their environment, and as it has changed they need to change again, and so it goes on as a constant process. Some people draw a distinction between complex adaptive systems and complex evolving systems. Where the former continuously adapt to the changes around them but do not learn from the process. And where the latter learn and evolve from each change enabling them to influence their environment, better predict likely changes in the future, and prepare for them accordingly.
- **Sub optimal**: A complex adaptive systems does not have to be perfect in order for it to thrive within its environment. It only has to be slightly better than its competitors and any energy used on being better than that is wasted energy. A complex adaptive systems once it has reached the state of being good enough will trade off increased efficiency every time in favour of greater effectiveness.
- **Requisite Variety**: The greater the variety within the system the stronger it is. In fact ambiguity and paradox abound in complex adaptive systems which use contradictions to create new possibilities to co-evolve with their environment. Democracy is a good example in that its strength is derived from its tolerance and even insistence in a variety of political perspectives.
- **Connectivity**: The ways in which the agents in a system connect and relate to one another is critical to the survival of the system, because it is from these connections that the patterns are formed and the feedback disseminated. The relationships between the agents are generally more important than the agents themselves.

- **Simple Rules**: Complex adaptive systems are not complicated. The emerging patterns may have a rich variety, but like a kaleidoscope the rules governing the function of the system are quite simple. A classic example is that all the water systems in the world, all the streams, rivers, lakes, oceans, waterfalls etc with their infinite beauty, power and variety are governed by the simple principle that water finds its own level.
- **Iteration**: Small changes in the initial conditions of the system can have significant effects after they have passed through the emergence - feedback loop a few times (often referred to as the butterfly effect). A rolling snowball for example gains on each roll much more snow than it did on the previous roll and very soon a fist sized snowball becomes a giant one.
- **Self Organising**: There is no hierarchy of command and control in a complex adaptive system. There is no planning or managing, but there is a constant re-organising to find the best fit with the environment. A classic example is that if one were to take any western town and add up all the food in the shops and divide by the number of people in the town there will be near enough two weeks supply of food, but there is no food plan, food manager or any other formal controlling process. The system is continually self organising through the process of emergence and feedback.
- **Edge of Chaos**: Complexity theory is not the same as chaos theory, which is derived from mathematics. But chaos does have a place in complexity theory in that systems exist on a spectrum ranging from equilibrium to chaos. A system in equilibrium does not have the internal dynamics to enable it to respond to its environment and will slowly (or quickly) die. A system in chaos ceases to function as a system. The most productive state to be in is at the edge of chaos where there is maximum variety and creativity, leading to new possibilities.
- **Nested Systems**: Most systems are nested within other systems and many systems are systems of smaller systems. If we take the example in self organising above and consider a food shop. The shop is itself a system with its staff, customers, suppliers, and neighbours. It also belongs within the food system of that town and the larger food system of that country. It belongs to the retail system locally and nationally and the economy system locally and nationally, and probably many more. Therefore it is part of many different systems most of which are themselves part of other systems.

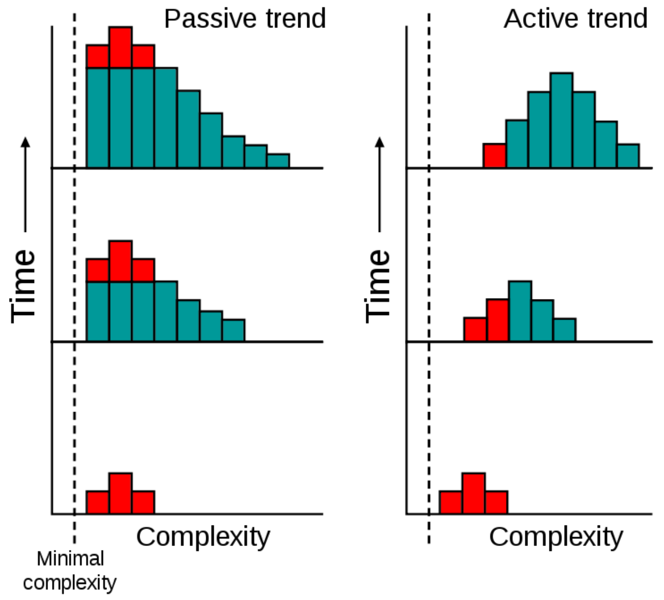
Management

When used in the management of people, CAS includes [1] setting appropriate containers, [2] understanding significant differences, and [3] facilitating transformation exchanges. In a CAS, managers set guidelines for workers to interpret, and use to self-organize.

Evolution of complexity

Living organisms are complex adaptive systems. Although complexity is hard to quantify in biology, evolution has produced some remarkably complex organisms.[5] This observation has led to the common misconception of evolution being progressive and leading towards what are viewed as "higher organisms".[6]

If this were generally true, evolution would possess an active trend towards complexity. As shown below, in this type of process the value of the most common amount of complexity would increase over time.[7] Indeed, some artificial life simulations have suggested that the generation of CAS is an inescapable feature of evolution.[8] [9]



Passive versus active trends in the evolution of complexity. CAS at the beginning of the processes are colored red. Changes in the number of systems are shown by the height of the bars, with each set of graphs moving up in a time series.

However, the idea of a general trend towards complexity in evolution can also be explained through a passive process.[7] This involves an increase in variance but the most common value, the mode, does not change. Thus, the maximum level of complexity increases over time, but only as an indirect product of there being more organisms in total. This type of random process is also called a bounded random walk.

In this hypothesis, the apparent trend towards more complex organisms is an illusion resulting from concentrating on the small number of large, very complex organisms that inhabit the right-hand tail of the complexity distribution and ignoring simpler and much more common organisms. This passive model emphasizes that the overwhelming majority of species are microscopic prokaryotes,[10] which comprise about half the world's biomass[11] and constitute the vast majority of Earth's biodiversity.[12] Therefore, simple life remains dominant on Earth, and complex life appears more diverse only because of sampling bias.

This lack of an overall trend towards complexity in biology does not preclude the existence of forces driving systems towards complexity in a subset of cases. These minor trends are balanced by other evolutionary pressures that drive systems towards less complex states.

See also

- Agent-based model
- Artificial life
- Center for Complex Systems and Brain Sciences
- Center for Social Dynamics & Complexity (CSDC) at Arizona State University [13]
- Cognitive Science
- Command and Control Research Program
- Complex system
- Computational Sociology
- Enterprise systems engineering
- Generative sciences
- Santa Fe Institute
- Simulated reality
- Sociology and complexity science
- Swarm Development Group

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External links

- Complexity Digest [20] comprehensive digest of latest CAS related news and research.
- DNA Wales Research Group [21] Current Research in Organisational change CAS/CES related news and free research data. Also linked to the Business Doctor & BBC documentary series
- A description [22] of complex adaptive systems on the Principia Cybernetica Web.
- Quick reference [23] single-page description of the 'world' of complexity and related ideas hosted by the Center for the Study of Complex Systems at the University of Michigan.
- Complex systems research network [24]
- The Open Agent-Based Modeling Consortium [25]

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[3] Complexity in Social Science glossary (http://www.irit.fr/COSI/glossary/fulllist.php?letter=C) a research training project of the European Commission

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[13] http://csdc.asu.edu/

[14] http://arxiv.org/abs/nlin/0506059

[15] http://www.hpl.hp.com/techreports/2004/HPL-2004-187.html

[16] http://www.foresight.gov.uk/OurWork/CompletedProjects/IIS/Docs/ComplexityandEmergentBehaviour.asp

[17] http://www.foresight.gov.uk/

[18] http://www.kk.org/outofcontrol/contents.php

[19] http://homepage.ntlworld.com/m.pharoah/

[20] http://www.comdig.org/

[21] http://www.dnawales.co.uk/

[22] http://pespmc1.vub.ac.be/CAS.html

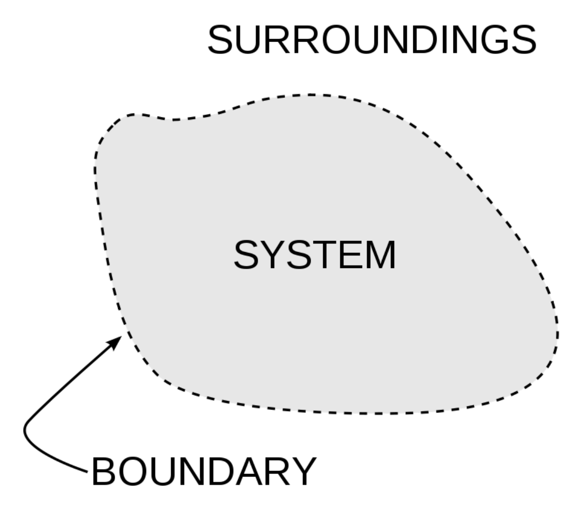
[23] http://bactra.org/notebooks/complexity.html

[24] http://www.complexsystems.net.au/

[25] http://www.openabm.org/site/

System Theories and Dynamics

System



A schematic representation of a closed system and its boundary

System (from Latin *systēma*, in turn from Greek *σύστημα* systēma) is a set of interacting or interdependent entities forming an integrated whole.

The concept of an **'integrated whole**' can also be stated in terms of a system embodying a set of relationships which are differentiated from relationships of the set to other elements, and from relationships between an element of the set and elements not a part of the relational regime.

The scientific research field which is engaged in the study of the general properties of systems include systems theory, cybernetics, dynamical systems and complex systems. They investigate the abstract properties of the matter and organization, searching concepts and principles which are independent of the specific domain, substance, type, or temporal scales of existence.

Most systems share common characteristics, including:

- Systems have structure, defined by parts and their composition;
- Systems have behavior, which involves inputs, processing and outputs of material, energy or information;
- Systems have interconnectivity: the various parts of a system have functional as well as structural relationships between each other.
- Systems have by themselves functions or groups of functions

The term *system* may also refer to a set of rules that governs behavior or structure.

History

The word *system* in its meaning here, has a long history which can be traced back to Plato (*Philebus*), Aristotle (*Politics*) and Euclid (*Elements*). It had meant "total", "crowd" or "union" in even more ancient times, as it derives from the verb *sunìstemi*, uniting, putting together.

In the 19th century the first to develop the concept of a "system" in the natural sciences was the French physicist Nicolas Léonard Sadi Carnot who studied thermodynamics. In 1824 he studied what he called the *working substance* (system), i.e. typically a body of water vapor, in steam engines, in regards to the system's ability to do work when heat is applied to it. The working substance could be put in contact with either a boiler, a cold reservoir (a stream of cold water), or a piston (to which the working body could do work by pushing on it). In 1850, the German physicist Rudolf Clausius generalized this picture to include the concept of the surroundings and began to use the term "working body" when referring to the system.

One of the pioneers of the general systems theory was the biologist Ludwig von Bertalanffy. In 1945 he introduced *models, principles, and laws that apply to generalized systems or their subclasses, irrespective of their particular kind, the nature of their component elements, and the relation or 'forces' between them.*[1]

Significant development to the concept of a *system* was done by Norbert Wiener and Ross Ashby who pioneered the use of mathematics to study systems [2] [3] .

In the 1980s the term complex adaptive system was coined at the interdisciplinary Santa Fe Institute by John H. Holland, Murray Gell-Mann and others.

System concepts

Environment and boundaries

Systems theory views the world as a complex system of interconnected parts. We scope a system by defining its boundary; this means choosing which entities are inside the system and which are outside - part of the environment. We then make simplified representations (models) of the system in order to understand it and to predict or impact its future behavior. These models may define the structure and/or the behavior of the system.

Natural and man-made systems

There are natural and man-made (designed) systems. Natural systems may not have an apparent objective but their outputs can be interpreted as purposes. Man-made systems are made with purposes that are achieved by the delivery of outputs. Their parts must be related; they must be “designed to work as a coherent entity” - else they would be two or more distinct systems

Theoretical Framework

An open system exchanges matter and energy with its surroundings. Most systems are open systems; like a car, coffeemaker, or computer. A closed system exchanges energy, but not matter, with its environment; like Earth or the project Biosphere2 or 3. An isolated system exchanges neither matter nor energy with its environment; a theoretical example of which would be the universe.

Process and transformation process

A system can also be viewed as a bounded transformation process, that is, a process or collection of processes that transforms inputs into outputs. Inputs are consumed; outputs are produced. The concept of input and output here is very broad. E.g., an output of a passenger ship is the movement of people from departure to destination.

Subsystem

A *subsystem* is a set of elements, which is a system itself, and a part of a larger system.

Types of systems

Evidently, there are many types of systems that can be analyzed both quantitatively and qualitatively. For example, with an analysis of urban systems dynamics, [A.W. Steiss] [4] defines five intersecting systems, including the physical subsystem and behavioral system. For sociological models influenced by systems theory, where Kenneth D. Bailey [5] defines systems in terms of conceptual, concrete and abstract systems; either isolated, closed, or open, Walter F. Buckley [6] defines social systems in sociology in terms of mechanical, organic, and process models. Bela H. Banathy [7] cautions that with any inquiry into a system that understanding the type of system is crucial and defines Natural and Designed systems.

In offering these more global definitions, the author maintains that it is important not to confuse one for the other. The theorist explains that natural systems include sub-atomic systems, living systems, the solar system, the galactic system and the Universe. Designed systems are our creations, our physical structures, hybrid systems which include natural and designed systems, and our conceptual knowledge. The human element of organization and activities are emphasized with their relevant abstract systems and representations. A key consideration in making distinctions among various types of systems is to determine how much freedom the system has to select purpose, goals, methods, tools, etc. and how widely is the freedom to select itself distributed (or concentrated) in the system.

George J. Klir [8] maintains that no "classification is complete and perfect for all purposes," and defines systems in terms of abstract, real, and conceptual physical systems, bounded and unbounded systems, discrete to continuous, pulse to hybrid systems, et cetera. The interaction between systems and their environments are categorized in terms of relatively closed, and open systems. It seems most unlikely that an absolutely closed system can exist or, if it did, that it could be known by us. Important distinctions have also been made between hard and soft systems.[9] Hard systems are associated with areas such as systems engineering, operations research and quantitative systems analysis. Soft systems are commonly associated with concepts developed by Peter Checkland and Brian Wilson through Soft Systems Methodology (SSM) involving methods such as action research and emphasizing participatory designs. Where hard systems might be identified as more "scientific," the distinction between them is actually often hard to define.

Cultural system

A cultural system may be defined as the interaction of different elements of culture. While a cultural system is quite different from a social system, sometimes both systems together are referred to as the sociocultural system. A major concern in the social sciences is the problem of order. One way that social order has been theorized is according to the degree of integration of cultural and social factors.

Economic system

An economic system is a mechanism (social institution) which deals with the production, distribution and consumption of goods and services in a particular society. The economic system is composed of people, institutions and their relationships to resources, such as the convention of property. It addresses the problems of economics, like the allocation and scarcity of resources.

Application of the system concept

Systems modeling is generally a basic principle in engineering and in social sciences. The system is the representation of the entities under concern. Hence inclusion to or exclusion from system context is dependent of the intention of the modeler.

No model of a system will include all features of the real system of concern, and no model of a system must include all entities belonging to a real system of concern.

Systems in information and computer science

In computer science and information science, **system** could also be a method or an algorithm. Again, an example will illustrate: There are systems of counting, as with Roman numerals, and various systems for filing papers, or catalogues, and various library systems, of which the Dewey Decimal System is an example. This still fits with the definition of components which are connected together (in this case in order to facilitate the flow of information).

System can also be used referring to a framework, be it software or hardware, designed to allow software programs to run, see platform.

Systems in engineering and physics

In engineering and physics, a physical system is the portion of the universe that is being studied (of which a thermodynamic system is one major example). Engineering also has the concept of a system that refers to all of the parts and interactions between parts of a complex project. Systems engineering refers to the branch of engineering that studies how this type of system should be planned, designed, implemented, built, and maintained.

Systems in social and cognitive sciences and management research

Social and cognitive sciences recognize systems in human person models and in human societies. They include human brain functions and human mental processes as well as normative ethics systems and social/cultural behavioral patterns.

In management science, operations research and organizational development (OD), human organizations are viewed as **systems** (conceptual systems) of interacting components such as subsystems or system aggregates, which are carriers of numerous complex processes and organizational structures. Organizational development theorist Peter Senge developed the notion of organizations as systems in his book *The Fifth Discipline*.

Systems thinking is a style of thinking/reasoning and problem solving. It starts from the recognition of system properties in a given problem. It can be a leadership competency. Some people can *think globally while acting locally*. Such people consider the potential consequences of their decisions on other parts of larger systems. This is also a basis of systemic coaching in psychology.

Organizational theorists such as Margaret Wheatley have also described the workings of organizational systems in new metaphoric contexts, such as quantum physics, chaos theory, and the self-organization of systems.

Systems applied to strategic thinking

In 1988, military strategist, John A. Warden III introduced his Five Ring System model in his book, *The Air Campaign* contending that any complex system could be broken down into five concentric rings. Each ring—Leadership, Processes, Infrastructure, Population and Action Units—could be used to isolate key elements of any system that needed change. The model was used effectively by Air Force planners in the First Gulf War.[10] ,[11] ,[12] . In the late 1990s, Warden applied this five ring model to business strategy[13] .

See also

Examples of systems

- List of systems (WikiProject)
- Complex system
- Formal system
- Information system
- Meta-system
- Solar System
- Systems in human anatomy

Theories about systems

- Chaos theory
- Cybernetics
- Systems ecology
- Systems engineering
- Systems psychology
- Systems theory

Related topics

- Glossary of systems theory
- Complexity theory and organizations
- Network
- System of systems (engineering)
- Systems art

Further reading

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External links

- *Definitions of Systems and Models* [15] by Michael Pidwirny, 1999-2007.
- *Definitionen von "System" (1572-2002)* [16] by Roland Müller, 2001-2007 (most in German).

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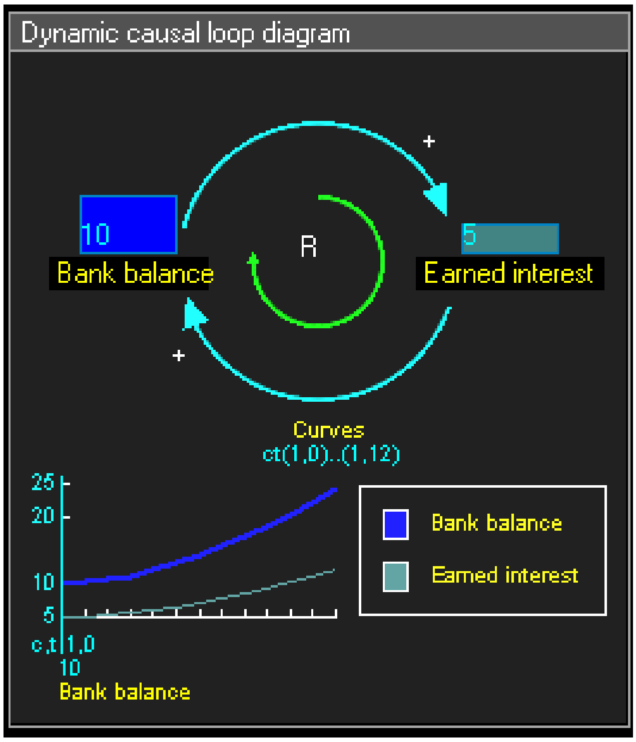
[1] 1945, *Zu einer allgemeinen Systemlehre,* Blätter für deutsche Philosophie, 3/4. (Extract in: Biologia Generalis, 19 (1949), 139-164.
[2] 1948, *Cybernetics: Or the Control and Communication in the Animal and the Machine.* Paris, France: Librairie Hermann & Cie, and Cambridge, MA: MIT Press.Cambridge, MA: MIT Press.
[3] 1956. *An Introduction to Cybernetics* (http://pespmc1.vub.ac.be/ASHBBOOK.html), Chapman & Hall.
[4] Steiss 1967, p.8-18.
[5] Bailey, 1994.
[6] Buckley, 1967.
[7] Banathy, 1997.
[8] Klir 1969, pp. 69-72
[9] Checkland 1997; Flood 1999.
[10] Warden, John A. III (1988). *The Air Campaign: Planning for Combat*. Washington, D.C.: National Defense University Press. ISBN 9781583481004.
[11] Warden, John A. III (September 1995). "Chapter 4: Air theory for the 21st century" (http://www.airpower.maxwell.af.mil/airchronicles/battle/chp4.html) (in *Air and Space Power Journal*). *Battlefield of the Future: 21st Century Warfare Issues*. United States Air Force. . Retrieved December 26, 2008.
[12] Warden, John A. III (1995). "Enemy as a System" (http://www.airpower.maxwell.af.mil/airchronicles/apj/apj95/spr95_files/warden.htm). *Airpower Journal* **Spring** (9): 40–55. . Retrieved 2009-03-25.
[13] Russell, Leland A.; Warden, John A. (2001). *Winning in FastTime: Harness the Competitive Advantage of Prometheus in Business and in Life*. Newport Beach, CA: GEO Group Press. ISBN 0971269718.
[14] http://www.newciv.org/ISSS_Primer/asem04bb.html
[15] http://www.physicalgeography.net/fundamentals/4b.html
[16] http://www.muellerscience.com/SPEZIALITAETEN/System/System_Definitionen.htm

Causal loop diagram



Example of positive reinforcing loop: *Bank balance* and *Earned interest*

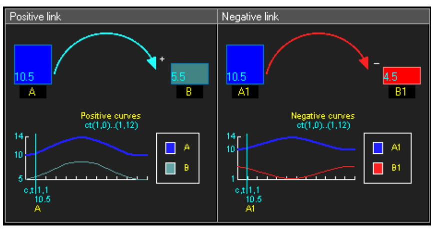
A **causal loop diagram** (CLD) is a diagram that aids in visualizing how interrelated variables affect one another. The diagram consists of a set of nodes representing the variables connected together. The relationships between these variables, represented by arrows, can be labelled as **positive** or **negative**.

Example of positive reinforcing loop:
The amount of the *Bank Balance* will affect the amount of the *Earned Interest*, as represented by the top blue arrow, pointing from *Bank Balance* to *Earned Interest*.
Since an increase in *Bank balance* results in an increase in *Earned Interest*, this link is positive, which is denoted with a ""+"".
The *Earned interest* gets added to the *Bank balance*, also a positive link, represented by the bottom blue arrow.
The causal effect between these nodes forms a **positive** reinforcing loop, represented by the green arrow, which is denoted with an "R".

Positive and negative causal links

- **Positive causal link** means that the two nodes change in the same direction, i.e. if the node in which the link starts decreases, the other node also decreases. Similarly, if the node in which the link starts increases, the other node increases.
- **Negative causal link** means that the two nodes change in opposite directions, i.e. if the node in which the link starts increases, then the other node decreases, and vice versa.

Example



Dynamic causal loop diagram: positive and negative links

Reinforcing and balancing loops

To determine if a causal loop is reinforcing or balancing, one can start with an assumption, e.g. "Node 1 increases" and follow the loop around. The loop is:

- **reinforcing** if, after going around the loop, one ends up with the same result as the initial assumption.
- **balancing** if the result contradicts the initial assumption.

Or to put it in other words:

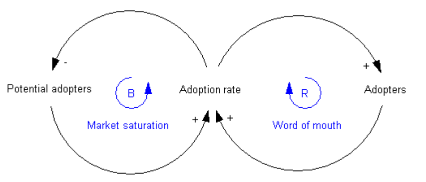
- reinforcing loops have an even number of negative links (zero also is even, see example above)
- balancing loops have an uneven number of negative links.

Identifying reinforcing and balancing loops is an important step for identifying *Reference Behaviour Patterns*, i.e. possible dynamic behaviours of the system.

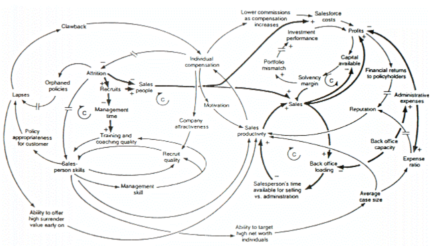
- Reinforcing loops are associated with exponential increases/decreases.
- Balancing loops are associated with reaching a plateau.

If the system has delays (often denoted by drawing a short line across the causal link), the system might fluctuate.

Example



Causal loop diagram of *Adoption* model, used to demonstrate systems dynamics



Causal loop diagram of a model examining the growth or decline of a life insurance company

See also

- System dynamics
- Positive feedback
- Negative feedback

External links

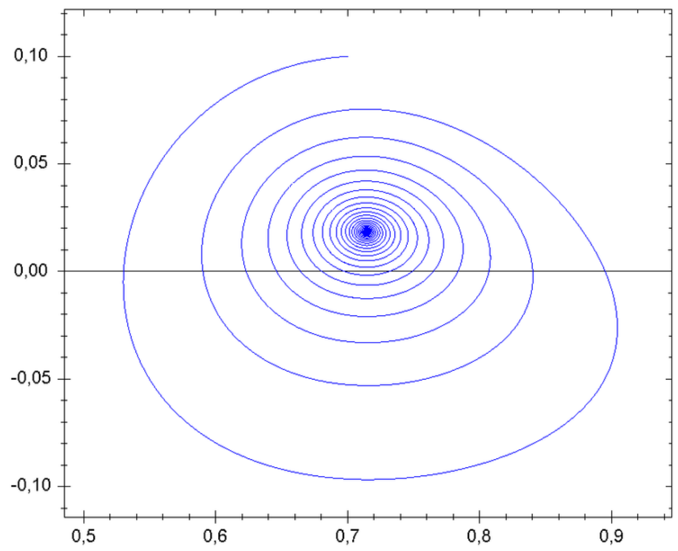
- System Models & Simulation [1] - Shows a causal-loop diagram of a dynamic system that is parameterized with data and equations, then simulated and graphed.
- WikiSD [2] the System Dynamics Society [3] Wiki

References

[1] http://www.excelsoftware.com/systemmodels.html
[2] http://www.systemdynamics.org/wiki/index.php/Main_Page
[3] http://systemdynamics.org/

Phase space

In mathematics and physics, a **phase space**, introduced by Willard Gibbs in 1901[1] , is a space in which all possible states of a system are represented, with each possible state of the system corresponding to one unique point in the phase space. For mechanical systems, the phase space usually consists of all possible values of position and momentum variables. A plot of position and momentum variables as a function of time is sometimes called a phase plot or a phase diagram. Phase diagram, however, is more usually reserved in the physical sciences for a diagram showing the various regions of stability of the thermodynamic phases of a chemical system, which consists of pressure, temperature, and composition.

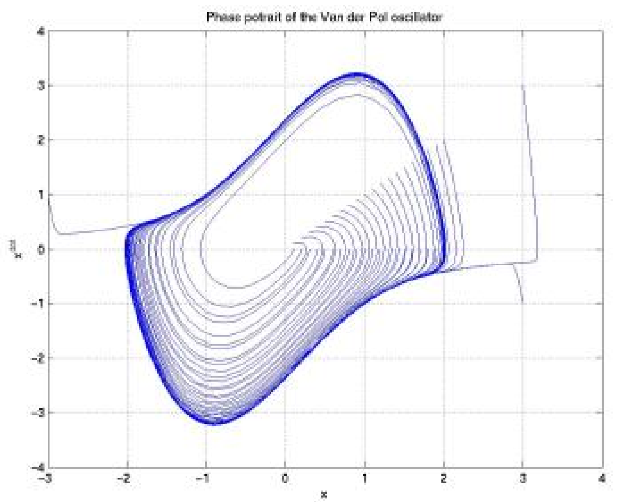


Phase space of a dynamical system with focal stability.

In a phase space, every degree of freedom or parameter of the system is represented as an axis of a multidimensional space. For every possible state of the system, or allowed combination of values of the system's parameters, a point is plotted in the multidimensional space. Often this succession of plotted points is analogous to the system's state evolving over time. In the end, the phase diagram represents all that the system can be, and its shape can easily elucidate qualities of the system that might not be obvious otherwise. A phase space may contain very many dimensions. For instance, a gas containing many molecules may require a separate dimension for each particle's *x*, *y* and *z* positions and momenta as well as any number of other properties.

In classical mechanics the phase space co-ordinates are the generalized coordinates q_i and their conjugate generalized momenta p_i. The motion of an ensemble of systems in this space is studied by classical statistical mechanics. The local density of points in such systems obeys Liouville's Theorem, and so can be taken as constant. Within the context of a model system in classical mechanics, the phase space coordinates of the system at any given time are composed of all of the system's dynamical variables. Because of this, it is possible to calculate the state of the system at any given time in the future or the past, through integration of Hamilton's or Lagrange's equations of motion. Furthermore, because each point in phase space lies on exactly one phase trajectory, no two phase trajectories can intersect.

For simple systems, such as a single particle moving in one dimension for example, there may be as few as two degrees of freedom, (typically, position and velocity), and a sketch of the phase portrait may give qualitative information about the dynamics of the system, such as the limit-cycle of the Van der Pol oscillator shown in the diagram.



Phase portrait of the Van der Pol oscillator

Here, the horizontal axis gives the position and vertical axis the velocity. As the system evolves, its state follows one of the lines (trajectories) on the phase diagram.

Classic examples of phase diagrams from chaos theory are :

- the Lorenz attractor
- parameter plane of complex quadratic polynomials with Mandelbrot set.

Quantum mechanics

In quantum mechanics, the coordinates *p* and *q* of phase space become hermitian operators in a Hilbert space, but may alternatively retain their classical interpretation, provided functions of them compose in novel algebraic ways (through Groenewold's 1946 star product). Every quantum mechanical observable corresponds to a unique function or distribution on phase space, and vice versa, as specified by Hermann Weyl (1927) and supplemented by John von Neumann (1931); Eugene Wigner (1932); and, in a grand synthesis, by H J Groenewold (1946). With J E Moyal (1949), these completed the foundations of phase-space quantization, a logically autonomous reformulation of quantum mechanics. Its modern abstractions include deformation quantization and geometric quantization.

Thermodynamics and statistical mechanics

In thermodynamics and statistical mechanics contexts, the term phase space has two meanings: It is used in the same sense as in classical mechanics. If a thermodynamical system consists of *N* particles, then a point in the *6N*-dimensional phase space describes the dynamical state of every particle in that system, as each particle is associated with three position variables and three momentum variables. In this sense, a point in phase space is said to be a microstate of the system. *N* is typically on the order of Avogadro's number, thus describing the system at a microscopic level is often impractical. This leads us to the use of phase space in a different sense.

The phase space can refer to the space that is parametrized by the *macroscopic* states of the system, such as pressure, temperature, etc. For instance, one can view the pressure-volume diagram or entropy-temperature diagrams as describing part of this phase space. A point in this phase space is correspondingly called a macrostate. There may easily be more than one microstate with the same macrostate. For example, for a fixed temperature, the system could have many dynamic configurations at the microscopic level. When used in this sense, a phase is a region of phase space where the system in question is in, for example, the liquid phase, or solid phase, etc.

Since there are many more microstates than macrostates, the phase space in the first sense is usually a manifold of much larger dimensions than the second sense. Clearly, many more parameters are required to register every detail of the system up to the molecular or atomic scale than to simply specify, say, the temperature or the pressure of the system.

See also

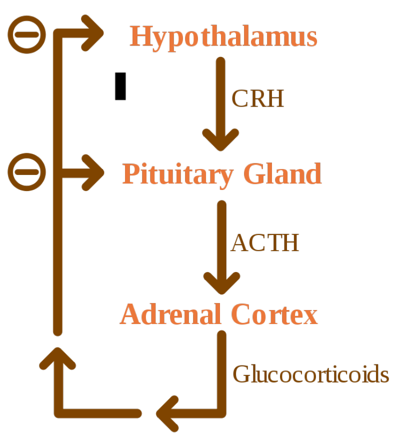
- Classical mechanics
- Dynamical system
- Molecular dynamics
- Hamiltonian mechanics
- Lagrangian mechanics
- Cotangent bundle
- Symplectic manifold
- Phase plane
- Phase space method
- Parameter space
- Optical Phase Space
- State space (controls) for information about state space (similar to phase state) in control engineering.
- State space (physics) for information about state space in physics
- State space for information about state space with discrete states in computer science.

References

[1] Findlay, Alex. The Phase Rule and its Applications. 3rd edition. pg 8. Longmans, Green and Co. 1911.

Negative feedback

Negative feedback occurs when the output of a system acts to oppose changes to the input of the system; with the result that the changes are attenuated. If the overall feedback of the system is negative, then the system will tend to be stable.



Most endocrine hormones are controlled by a physiologic negative feedback inhibition loop, such as the glucocorticoids secreted by the adrenal cortex. The hypothalamus secretes corticotropin-releasing hormone (CRH), which directs the anterior pituitary gland to secrete adrenocorticotropic hormone (ACTH). In turn, ACTH directs the adrenal cortex to secrete glucocorticoids, such as cortisol. Glucocorticoids not only perform their respective functions throughout the body but also negatively affect the release of further stimulating secretions of both the hypothalamus and the pituitary gland, effectively reducing the output of glucocorticoids once a sufficient amount has been released.[1]

Overview

In many physical and biological systems, qualitatively different influences can oppose each other. For example, in biochemistry, one set of chemicals drives the system in a given direction, whereas another set of chemicals drives it in an opposing direction. If one, or both of these opposing influences are non-linear, equilibrium point(s) result.

In biology, this process (generally biochemical) is often referred to as homeostasis; whereas in mechanics, the more common term is equilibrium.

In engineering, mathematics and the physical and biological sciences, common terms for the points around which the system gravitates include: attractors, stable states, eigenstates/eigenfunctions, equilibrium points, and setpoints.

Negative refers to the sign of the multiplier in mathematical models for feedback. In delta notation, - Δoutput is added to or mixed into the input. In multivariate systems, vectors help to illustrate how several influences can both partially complement and partially oppose each other.

In contrast, **positive feedback** is feedback in which the system responds so as to act to increase the magnitude of any particular perturbation, resulting in amplification of the original signal instead of stabilization. Any system where there is a net positive feedback will result in a runaway situation. Both positive and negative feedback require a feedback loop to operate.

Negative feedback is used to describe the act of reversing any discrepancy between desired and actual output.

Examples

Mechanical Engineering

Negative feedback was first implemented in the 16th Century with the invention of the centrifugal governor. Its operation is most easily seen in its use by James Watt to control the speed of his steam engine. Two heavy balls on an upright frame rotate at the same speed as the engine. As their speed increases they move outwards due to the centrifugal force. This causes them to lift a mechanism which closes the steam inlet valve and the engine slows. When the speed of the engine falls too far, the balls will move in the opposite direction and open the steam valve.

Control

Examples of the use of negative feedback to control its system are: thermostat control, phase-locked loop, hormonal regulation (see diagram above), and temperature regulation in animals.

A simple and practical example is a thermostat. When the temperature in a heated room reaches a certain upper limit the room heating is switched off so that the temperature begins to fall. When the temperature drops to a lower limit, the heating is switched on again. Provided the limits are close to each other, a steady room temperature is maintained. The same applies to a cooling system, such as an air conditioner, a refrigerator, or a freezer.

Biology & Chemistry

Some biological systems exhibit negative feedback such as the baroreflex in blood pressure regulation and erythropoiesis. Many biological process (e.g., in the human anatomy) use negative feedback. Examples of this are numerous, from the regulating of body temperature, to the regulating of blood glucose levels. The disruption of feedback loops can lead to undesirable results: in the case of blood glucose levels, if negative feedback fails, the glucose levels in the blood may begin to rise dramatically, thus resulting in diabetes.

For hormone secretion regulated by the negative feedback loop: when gland X releases hormone X, this stimulates target cells to release hormone Y. When there is an excess of hormone Y, gland X "senses" this and inhibits its release of hormone X.

Economics

In economics, automatic stabilisers are government programs which work as negative feedback to dampen fluctuations in real GDP.

Electronic amplifiers

The negative feedback amplifier was invented by Harold Stephen Black at Bell Laboratories in 1927, and patented by him in 1934. Fundamentally, all electronic devices (e.g. vacuum tubes, bipolar transistors, MOS transistors) exhibit some nonlinear behavior. Negative feedback corrects this by trading unused gain for higher linearity (lower distortion). An amplifier with too large an open-loop gain, possibly in a specific frequency range, will additionally produce too large a feedback signal in that same range. This feedback signal, when subtracted from the original input, will act to reduce the original input, also by "too large" an amount. This "too small" input will be amplified again by the "too large" open-loop gain, creating a signal that is "just right". The net result is a flattening of the amplifier's gain over all frequencies (desensitising). Though much more accurate, amplifiers with negative feedback can become unstable if not designed correctly, causing them to oscillate. Harry Nyquist of Bell Laboratories managed to work out a theory about how to make this behaviour stable.

Negative feedback is used in this way in many types of amplification systems to *stabilize* and improve their operating characteristics (see e.g., operational amplifiers).

See also

- Asymptotic gain model
- Biofeedback
- Control theory
- Cybernetics
- Nyquist stability criterion
- Stability criterion
- Step response
- Global Warming

External links

- http://www.biology-online.org/4/1_physiological_homeostasis.htm

References

[1] Raven, PH; Johnson, GB. *Biology*, Fifth Edition, Boston: Hill Companies, Inc. 1999. page 1058.

Information flow diagram

An **information flow diagram** (IFD) is an illustration of information flow throughout an organisation. An IFD shows the relationship between external and internal information flows between an organisation. It also shows the relationship between the internal departments and sub-systems.

An Information Flow Diagram is information about a system laid out in diagramatic form. Usually using "blobs" to explain in more details the system and sub-systems to elemental parts. Following on from this you can add in lines of how the information travels from one system to another. This is used in businesses, Government agencies, television and cinematic processes.

Overview

Peter Checkland, a British management scientist, identifies that information flows between the different elements that compose the system. He also defines a system as a 'community situated within an environment'.

IFD is useful for specifying the boundaries and scope of the system. The IFD shows the boundaries and scope of the system, it's interactions with its external entities, and the main flows of information within the system and within any complex subsystems.

The Information Flow Diagram (IFD) is one of the simplest tools used to document findings from the requirements determination process. They are used for a number of purposes: 1. to document the main flows of information around the organisation; 2. for the analyst to check that he/she has understood those flows and that none has been omitted; 3. the analyst may use them during the fact-finding process itself as an accurate and efficient way to document findings as they are identified; 4. as a high-level (not detailed) tool to document information flows within the organisation as a whole or a lower-level tool to document an individual functional area of the business.

See also

- Information systems
- Systems thinking

System theory

Systems theory is an interdisciplinary theory about the nature of complex systems in nature, society, and science, and is a framework by which one can investigate and/or describe any group of objects that work together to produce some result. This could be a single organism, any organization or society, or any electro-mechanical or informational artifact. As a technical and general academic area of study it predominantly refers to the science of systems that resulted from Bertalanffy's General System Theory (GST), among others, in initiating what became a project of systems research and practice. Systems theoretical approaches were later appropriated in other fields, such as in the structural functionalist sociology of Talcott Parsons and Niklas Luhmann.

Overview

Margaret Mead was an influential figure in systems theory.

Contemporary ideas from systems theory have grown with diversified areas, exemplified by the work of Béla H. Bánáthy, ecological systems with Howard T. Odum, Eugene Odum and Fritjof Capra, organizational theory and management with individuals such as Peter Senge, interdisciplinary study with areas like Human Resource Development from the work of Richard A. Swanson, and insights from educators such as Debora Hammond and Alfonso Montuori. As a transdisciplinary, interdisciplinary and multiperspectival domain, the area brings together principles and concepts from ontology, philosophy of science, physics, computer science, biology, and engineering as well as geography, sociology, political science, psychotherapy (within family systems therapy) and economics among others. Systems theory thus serves as a bridge for interdisciplinary dialogue between autonomous areas of study as well as within the area of systems science itself.

In this respect, with the possibility of misinterpretations, von Bertalanffy [1] believed a general theory of systems "should be an important regulative device in science," to guard against superficial analogies that "are useless in science and harmful in their practical consequences." Others remain closer to the direct systems concepts developed by the original theorists. For example, Ilya Prigogine, of the Center for Complex Quantum Systems at the University of Texas, Austin, has studied emergent properties, suggesting that they offer analogues for living systems. The theories of autopoiesis of Francisco Varela and Humberto Maturana are a further development in this field. Important names in contemporary systems science include Russell Ackoff, Béla H. Bánáthy, Anthony Stafford Beer, Peter Checkland, Robert L. Flood, Fritjof Capra, Michael C. Jackson, Edgar Morin and Werner Ulrich, among others.

With the modern foundations for a general theory of systems following the World Wars, Ervin Laszlo, in the preface for Bertalanffy's book *Perspectives on General System Theory*, maintains that the translation of "general system theory" from German into English has "wrought a certain amount of havoc" [2] . The preface explains that the original concept of a general system theory was "*Allgemeine Systemtheorie* (or *Lehre*)", pointing out the fact that "Theorie" (or "Lehre") just as "Wissenschaft" (translated Scholarship), "has a much broader meaning in German than the closest English words ‘theory’ and ‘science’" [2] . With these ideas referring to an organized body of knowledge

and "any systematically presented set of concepts, whether they are empirical, axiomatic, or philosophical", "Lehre" is associated with theory and science in the etymology of general systems, but also does not translate from the German very well; "teaching" is the "closest equivalent", but "sounds dogmatic and off the mark" [2] . While many of the root meanings for the idea of a "general systems theory" might have been lost in the translation and many were led to believe that the systems theorists had articulated nothing but a pseudoscience, systems theory became a nomenclature that early investigators used to describe the interdependence of relationships in organization by defining a new way of thinking about science and scientific paradigms.

A system from this frame of reference is composed of regularly interacting or interrelating groups of activities. For example, in noting the influence in organizational psychology as the field evolved from "an individually oriented industrial psychology to a systems and developmentally oriented organizational psychology," it was recognized that organizations are complex social systems; reducing the parts from the whole reduces the overall effectiveness of organizations [3] . This is at difference to conventional models that center on individuals, structures, departments and units separate in part from the whole instead of recognizing the interdependence between groups of individuals, structures and processes that enable an organization to function. Laszlo [4] explains that the new systems view of organized complexity went "one step beyond the Newtonian view of organized simplicity" in reducing the parts from the whole, or in understanding the whole without relation to the parts. The relationship between organizations and their environments became recognized as the foremost source of complexity and interdependence. In most cases the whole has properties that cannot be known from analysis of the constituent elements in isolation. Béla H. Bánáthy, who argued - along with the founders of the systems society - that "the benefit of humankind" is the purpose of science, has made significant and far-reaching contributions to the area of systems theory. For the Primer Group at ISSS, Bánáthy defines a perspective that iterates this view:

> The systems view is a world-view that is based on the discipline of SYSTEM INQUIRY. Central to systems inquiry is the concept of SYSTEM. In the most general sense, system means a configuration of parts connected and joined together by a web of relationships. The Primer group defines system as a family of relationships among the members acting as a whole. Von Bertalanffy defined system as "elements in standing relationship.
>
> —[5]

Similar ideas are found in learning theories that developed from the same fundamental concepts, emphasizing that understanding results from knowing concepts both in part and as a whole. In fact, Bertalanffy's organismic psychology paralleled the learning theory of Jean Piaget.[6] Interdisciplinary perspectives are critical in breaking away from industrial age models and thinking where history is history and math is math segregated from the arts and music separate from the sciences and never the twain shall meet [7] . The influential contemporary work of Peter Senge [8] provides detailed discussion of the commonplace critique of educational systems grounded in conventional assumptions about learning, including the problems with fragmented knowledge and lack of holistic learning from the "machine-age thinking" that became a "model of school separated from daily life." It is in this way that systems theorists attempted to provide alternatives and an evolved ideation from orthodox theories with individuals such as Max Weber, Émile Durkheim in sociology and Frederick Winslow Taylor in scientific management, which were grounded in classical assumptions [9] . The theorists sought holistic methods by developing systems concepts that could be integrated with different areas.

The contradiction of reductionism in conventional theory (which has as its subject a single part) is simply an example of changing assumptions. The emphasis with systems theory shifts from parts to the organization of parts, recognizing interactions of the parts are not "static" and constant but "dynamic" processes. Conventional closed systems were questioned with the development of open systems perspectives. The shift was from absolute and universal authoritative principles and knowledge to relative and general conceptual and perceptual knowledge [10] , still in the tradition of theorists that sought to provide means in organizing human life. Meaning, the history of ideas that preceded were rethought not lost. Mechanistic thinking was particularly critiqued, especially the industrial-age

mechanistic metaphor of the mind from interpretations of Newtonian mechanics by Enlightenment philosophers and later psychologists that laid the foundations of modern organizational theory and management by the late 19th century [11] . Classical science had not been overthrown, but questions arose over core assumptions that historically influenced organized systems, within both social and technical sciences.

History

TIMELINE

Precursors

- Herbert Spencer (1820–1903), Vilfredo Pareto (1848–1923), Émile Durkheim (1858–1917), Alexander Bogdanov (1873–1928), Nicolai Hartmann (1882–1950), Robert Maynard Hutchins (1929–1951), among others

Pioneers

- 1946-1953 Macy conferences
- 1948 Norbert Wiener publishes *Cybernetics or Control and Communication in the Animal and the Machine*
- 1954 Ludwig von Bertalanffy, Anatol Rapoport, Ralph W. Gerard, Kenneth Boulding establish Society for the Advancement of General Systems Theory, in 1956 renamed to Society for General Systems Research.
- 1955 W. Ross Ashby publishes *Introduction to Cybernetics*
- 1968 Ludwig von Bertalanffy publishes *General System theory: Foundations, Development, Applications*

Developments

- 1970-1980s Second-order cybernetics developed by Heinz von Foerster, Gregory Bateson, Humberto Maturana and others
- 1970s Catastrophe theory (René Thom, E.C. Zeeman) Dynamical systems in mathematics.
- 1980s Chaos theory David Ruelle, Edward Lorenz, Mitchell Feigenbaum, Steve Smale, James A. Yorke
- 1986 Context theory Anthony Wilden
- 1988 International Society for Systems Science
- 1990 Complex adaptive systems (CAS) John H. Holland, Murray Gell-Mann, W. Brian Arthur

Whether considering the first systems of written communication with Sumerian cuneiform to Mayan numerals, or the feats of engineering with the Egyptian pyramids, systems thinking in essence dates back to antiquity. Differentiated from Western rationalist traditions of philosophy, C. West Churchman often identified with the I Ching as a systems approach sharing a frame of reference similar to pre-Socratic philosophy and Heraclitus [12] . Von Bertalanffy traced systems concepts to the philosophy of G.W. von Leibniz and Nicholas of Cusa's *coincidentia oppositorum*. While modern systems are considerably more complicated, today's systems are embedded in history.

Systems theory as an area of study specifically developed following the World Wars from the work of Ludwig von Bertalanffy, Anatol Rapoport, Kenneth E. Boulding, William Ross Ashby, Margaret Mead, Gregory Bateson, C. West Churchman and others in the 1950s, specifically catalyzed by the cooperation in the Society for General Systems Research. Cognizant of advances in science that questioned classical assumptions in the organizational sciences, Bertalanffy's idea to develop a theory of systems began as early as the interwar period, publishing "An Outline for General Systems Theory" in the *British Journal for the Philosophy of Science*, Vol 1, No. 2, by 1950. Where assumptions in Western science from Greek thought with Plato and Aristotle to Newton's *Principia* have historically influenced all areas from the hard to social sciences (see David Easton's seminal development of the "political system" as an analytical construct), the original theorists explored the implications of twentieth century advances in terms of systems.

Subjects like complexity, self-organization, connectionism and adaptive systems had already been studied in the 1940s and 1950s. In fields like cybernetics, researchers like Norbert Wiener, William Ross Ashby, John von Neumann and Heinz von Foerster examined complex systems using mathematics. John von Neumann discovered cellular automata and self-reproducing systems, again with only pencil and paper. Aleksandr Lyapunov and Jules

Henri Poincaré worked on the foundations of chaos theory without any computer at all. At the same time Howard T. Odum, the radiation ecologist, recognised that the study of general systems required a language that could depict energetics and kinetics at any system scale. Odum developed a general systems, or Universal language, based on the circuit language of electronics to fulfill this role, known as the Energy Systems Language. Between 1929-1951, Robert Maynard Hutchins at the University of Chicago had undertaken efforts to encourage innovation and interdisciplinary research in the social sciences, aided by the Ford Foundation with the interdisciplinary Division of the Social Sciences established in 1931[13] . Numerous scholars had been actively engaged in ideas before (Tectology of Alexander Bogdanov published in 1912-1917 is a remarkable example), but in 1937 von Bertalanffy presented the general theory of systems for a conference at the University of Chicago.

The systems view was based on several fundamental ideas. First, all phenomena can be viewed as a web of relationships among elements, or a system. Second, all systems, whether electrical, biological, or social, have common patterns, behaviors, and properties that can be understood and used to develop greater insight into the behavior of complex phenomena and to move closer toward a unity of science. System philosophy, methodology and application are complementary to this science [2] . By 1956, the Society for General Systems Research was established, renamed the International Society for Systems Science in 1988. The Cold War affected the research project for systems theory in ways that sorely disappointed many of the seminal theorists. Some began to recognize theories defined in association with systems theory had deviated from the initial General Systems Theory (GST) view[14] . The economist Kenneth Boulding, an early researcher in systems theory, had concerns over the manipulation of systems concepts. Boulding concluded from the effects of the Cold War that abuses of power always prove consequential and that systems theory might address such issues [15] . Since the end of the Cold War, there has been a renewed interest in systems theory with efforts to strengthen an ethical view.

Developments in system theories

General systems research and systems inquiry

Many early systems theorists aimed at finding a general systems theory that could explain all systems in all fields of science. The term goes back to Bertalanffy's book titled "*General System theory: Foundations, Development, Applications*" from 1968[6] . Von Bertalanffy tells that he developed the "allgemeine Systemtheorie" since 1937 in talks and since 1946 with publications.[16]

Von Bertalanffy's objective was to bring together under one heading the organismic science that he had observed in his work as a biologist. His desire was to use the word "system" to describe those principles which are common to systems in general. In GST, he writes:

> ...there exist models, principles, and laws that apply to generalized systems or their subclasses, irrespective of their particular kind, the nature of their component elements, and the relationships or "forces" between them. It seems legitimate to ask for a theory, not of systems of a more or less special kind, but of universal principles applying to systems in general.
> —[17]

Ervin Laszlo [18] in the preface of von Bertalanffy's book *Perspectives on General System Theory..* [19]

> Thus when von Bertalanffy spoke of Allgemeine Systemtheorie it was consistent with his view that he was proposing a new perspective, a new way of doing science. It was not directly consistent with an interpretation often put on "general system theory", to wit, that it is a (scientific) "theory of general systems." To criticize it as such is to shoot at straw men. Von Bertalanffy opened up something much broader and of much greater significance than a single theory (which, as we now know, can always be falsified and has usually an ephemeral existence): he created a new paradigm for the development of theories.

Ludwig von Bertalanffy outlines systems inquiry into three major domains: Philosophy, Science, and Technology. In his work with the Primer Group, Béla H. Bánáthy generalized the domains into four integratable domains of systemic inquiry:

Domain	Description
Philosophy	the ontology, epistemology, and axiology of systems;
Theory	a set of interrelated concepts and principles applying to all systems
Methodology	the set of models, strategies, methods, and tools that instrumentalize systems theory and philosophy
Application	the application and interaction of the domains

These operate in a recursive relationship, he explained. Integrating Philosophy and Theory as Knowledge, and Method and Application as action, Systems Inquiry then is knowledgeable action.[20]

Cybernetics

The term cybernetics derives from a Greek word which meant steersman, and which is the origin of English words such as "govern". Cybernetics is the study of feedback and derived concepts such as communication and control in living organisms, machines and organisations. Its focus is how anything (digital, mechanical or biological) processes information, reacts to information, and changes or can be changed to better accomplish the first two tasks.

The terms "systems theory" and "cybernetics" have been widely used as synonyms. Some authors use the term *cybernetic* systems to denote a proper subset of the class of general systems, namely those systems that include feedback loops. However Gordon Pask's differences of eternal interacting actor loops (that produce finite products) makes general systems a proper subset of cybernetics. According to Jackson (2000), von Bertalanffy promoted an embryonic form of general system theory (GST) as early as the 1920s and 1930s but it was not until the early 1950s it became more widely known in scientific circles.

Threads of cybernetics began in the late 1800s that led toward the publishing of seminal works (e.g., Wiener's *Cybernetics* in 1948 and von Bertalanffy's *General Systems Theory* in 1968). Cybernetics arose more from engineering fields and GST from biology. If anything it appears that although the two probably mutually influenced each other, cybernetics had the greater influence. Von Bertalanffy (1969) specifically makes the point of distinguishing between the areas in noting the influence of cybernetics: "Systems theory is frequently identified with cybernetics and control theory. This again is incorrect. Cybernetics as the theory of control mechanisms in technology and nature is founded on the concepts of information and feedback, but as part of a general theory of systems;" then reiterates: "the model is of wide application but should not be identified with 'systems theory' in general", and that "warning is necessary against its incautious expansion to fields for which its concepts are not made." (17-23). Jackson (2000) also claims von Bertalanffy was informed by Alexander Bogdanov's three volume *Tectology* that was published in Russia between 1912 and 1917, and was translated into German in 1928. He also states it is clear to Gorelik (1975) that the "conceptual part" of general system theory (GST) had first been put in place by Bogdanov. The similar position is held by Mattessich (1978) and Capra (1996). Ludwig von Bertalanffy never even mentioned Bogdanov in his works, which Capra (1996) finds "surprising".

Cybernetics, catastrophe theory, chaos theory and complexity theory have the common goal to explain complex systems that consist of a large number of mutually interacting and interrelated parts in terms of those interactions. Cellular automata (CA), neural networks (NN), artificial intelligence (AI), and artificial life (ALife) are related fields, but they do not try to describe general (universal) complex (singular) systems. The best context to compare the different "C"-Theories about complex systems is historical, which emphasizes different tools and methodologies, from pure mathematics in the beginning to pure computer science now. Since the beginning of chaos theory when Edward Lorenz accidentally discovered a strange attractor with his computer, computers have become an indispensable source of information. One could not imagine the study of complex systems without the use of

computers today.

Complex adaptive systems

Complex adaptive systems are special cases of complex systems. They are *complex* in that they are diverse and made up of multiple interconnected elements and *adaptive* in that they have the capacity to change and learn from experience. The term *complex adaptive systems* was coined at the interdisciplinary Santa Fe Institute (SFI), by John H. Holland, Murray Gell-Mann and others. However, the approach of the complex adaptive systems does not take into account the adoption of information which enables people to use it.

CAS ideas and models are essentially evolutionary. Accordingly, the theory of complex adaptive systems bridges developments of the system theory with the ideas of 'generalized Darwinism', which suggests that Darwinian principles of evolution help explain a wide range of phenomena.

Applications of system theories

Living systems theory

Living systems theory is an offshoot of von Bertalanffy's general systems theory, created by James Grier Miller, which was intended to formalize the concept of "life". According to Miller's original conception as spelled out in his magnum opus *Living Systems*, a "living system" must contain each of 20 "critical subsystems", which are defined by their functions and visible in numerous systems, from simple cells to organisms, countries, and societies. In *Living Systems* Miller provides a detailed look at a number of systems in order of increasing size, and identifies his subsystems in each.

James Grier Miller (1978) wrote a 1,102-page volume to present his living systems theory. He constructed a general theory of living systems by focusing on concrete systems—nonrandom accumulations of matter-energy in physical space-time organized into interacting, interrelated subsystems or components. Slightly revising the original model a dozen years later, he distinguished eight "nested" hierarchical levels in such complex structures. Each level is "nested" in the sense that each higher level contains the next lower level in a nested fashion.

Organizational theory

Kurt Lewin attended the Macy conferences and is commonly identified as the founder of the movement to study groups scientifically.

The systems framework is also fundamental to organizational theory as organizations are complex dynamic goal-oriented processes. One of the early thinkers in the field was Alexander Bogdanov, who developed his Tectology, a theory widely considered a precursor of von Bertalanffy's GST, aiming to model and design human organizations (see Mattessich 1978, Capra 1996). Kurt Lewin was particularly influential in developing the systems perspective within organizational theory and coined the term "systems of ideology", from his frustration with behavioral psychologies that became an obstacle to sustainable work in psychology [21] . Jay Forrester with his work in dynamics and management alongside numerous theorists including Edgar Schein that followed in their tradition since the Civil Rights Era have also been influential.

The systems to organizations relies heavily upon achieving negative entropy through openness and feedback. A systemic view on organizations is transdisciplinary and integrative. In other words, it transcends the perspectives of individual disciplines, integrating them on the basis of a common "code", or more exactly, on the basis of the formal apparatus provided by systems theory. The systems approach gives primacy to the interrelationships, not to the elements of the system. It is from these dynamic interrelationships that new properties of the system emerge. In recent years, *systems thinking* has been developed to provide techniques for studying systems in holistic ways to supplement traditional reductionistic methods. In this more recent tradition, systems theory in organizational studies is considered by some as a humanistic extension of the natural sciences.

Software and computing

In the 1960s, systems theory was adopted by the post John Von Neumann computing and information technology field and, in fact, formed the basis of structured analysis and structured design (see also Larry Constantine, Tom DeMarco and Ed Yourdon). It was also the basis for early software engineering and computer-aided software engineering principles.

By the 1970s, General Systems Theory (GST) was the fundamental underpinning of most commercial software design techniques, and by the 1980, W. Vaughn Frick and Albert F. Case, Jr. had used GST to design the "missing link" transformation from system analysis (defining what's needed in a system) to system design (what's actually implemented) using the Yourdon/DeMarco notation. These principles were incorporated into computer-aided software engineering tools delivered by Nastec Corporation, Transform Logic, Inc., KnowledgeWare (see Fran Tarkenton and James Martin), Texas Instruments, Arthur Andersen and ultimately IBM Corporation.

Sociology and Sociocybernetics

Systems theory has also been developed within sociology. An important figure in the sociological systems perspective as developed from GST is Walter Buckley (who from Bertalanffy's theory). Niklas Luhmann (see Luhmann 1994) is also predominant in the literatures for sociology and systems theory. Miller's living systems theory was particularly influential in sociology from the time of the early systems movement. Models for dynamic equilibrium in systems analysis that contrasted classical views from Talcott Parsons and George Homans were influential in integrating concepts with the general movement. With the renewed interest in systems theory on the rise since the 1990s, Bailey (1994) notes the concept of systems in sociology dates back to Auguste Comte in the 19th century, Herbert Spencer and Vilfredo Pareto, and that sociology was readying into its centennial as the new systems theory was emerging following the World Wars. To explore the current inroads of systems theory into sociology (primarily in the form of complexity science) see sociology and complexity science.

In sociology, members of Research Committee 51 of the International Sociological Association (which focuses on sociocybernetics), have sought to identify the sociocybernetic feedback loops which, it is argued, primarily control the operation of society. On the basis of research largely conducted in the area of education, Raven (1995) has, for example, argued that it is these sociocybernetic processes which consistently undermine well intentioned public action and are currently heading our species, at an exponentially increasing rate, toward extinction. See sustainability. He suggests that an understanding of these systems processes will allow us to generate the kind of (non "common-sense") targeted interventions that are required for things to be otherwise - i.e. to halt the destruction of the planet.

System dynamics

System Dynamics was founded in the late 1950s by Jay W. Forrester of the MIT Sloan School of Management with the establishment of the MIT System Dynamics Group. At that time, he began applying what he had learned about systems during his work in electrical engineering to everyday kinds of systems. Determining the exact date of the founding of the field of system dynamics is difficult and involves a certain degree of arbitrariness. Jay W. Forrester joined the faculty of the Sloan School at MIT in 1956, where he then developed what is now System Dynamics. The first published article by Jay W. Forrester in the Harvard Business Review on "Industrial Dynamics", was published in 1958. The members of the System Dynamics Society have chosen 1957 to mark the occasion as it is the year in which the work leading to that article, which described the dynamics of a manufacturing supply chain, was done.

As an aspect of systems theory, *system dynamics* is a method for understanding the dynamic behavior of complex systems. The basis of the method is the recognition that the structure of any system — the many circular, interlocking, sometimes time-delayed relationships among its components — is often just as important in determining its behavior as the individual components themselves. Examples are chaos theory and social dynamics. It is also claimed that, because there are often properties-of-the-whole which cannot be found among the properties-of-the-elements, in some cases the behavior of the whole cannot be explained in terms of the behavior of the parts. An example is the properties of these letters which when considered together can give rise to meaning which does not exist in the letters by themselves. This further explains the integration of tools, like language, as a more parsimonious process in the human application of easiest path adaptability through interconnected systems.

Systems engineering

Systems Engineering is an interdisciplinary approach and means for enabling the realization and deployment of successful systems. It can be viewed as the application of engineering techniques to the engineering of systems, as well as the application of a systems approach to engineering efforts.[22] Systems Engineering integrates other disciplines and specialty groups into a team effort, forming a structured development process that proceeds from concept to production to operation and disposal. Systems Engineering considers both the business and the technical needs of all customers, with the goal of providing a quality product that meets the user needs.[23]

Systems psychology

Systems psychology is a branch of psychology that studies human behaviour and experience in complex systems. It is inspired by systems theory and systems thinking, and based on the theoretical work of Roger Barker, Gregory Bateson, Humberto Maturana and others. It is an approach in psychology, in which groups and individuals, are considered as systems in homeostasis. Systems psychology "includes the domain of engineering psychology, but in addition is more concerned with societal systems and with the study of motivational, affective, cognitive and group behavior than is engineering psychology."[24] In systems psychology "characteristics of organizational behaviour for example individual needs, rewards, expectations, and attributes of the people interacting with the systems are considered in the process in order to create an effective system".[25] . The Systems psychology includes an illusion of homeostatic systems, although most of the living systems are in a continuous disequilibrium of various degrees.

See also

- List of types of systems theory
- Cybernetics
- Emergence
- Glossary of systems theory
- Holism
- Meta-systems
- Open and Closed Systems in Social Science
- Social rule system theory
- Sociology and complexity science
- Systemantics
- System engineering
- Systems psychology
- Systemics
- Systems theory in archaeology
- Systems theory in anthropology
- Systems theory in political science
- Systems thinking
- World-systems theory
- Systematics - study of multi-term systems

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External links

- Systems theory [31] at Principia Cybernetica Web

Organizations

- International Society for the System Sciences [32]
- New England Complex Systems Institute [33]
- System Dynamics Society [34]

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[9] (Bailey 1994: 3-8; see also Owens 2004)
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[11] (Bailey 1994; Flood 1997; Checkland 1999; Laszlo 1972)
[12] (Hammond 2003: 12-13)
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Systems thinking

Systems thinking is the process of understanding how things influence one another within a whole. In nature systems thinking examples include ecosystems in which various elements such as air, water, movement, plant and animals work together to survive or perish. In organizations, systems consist of people, structures, and processes that work together to make an organization healthy or unhealthy.

Systems thinking has been defined as an approach to problem solving, by viewing "problems" as parts of an overall system, rather than reacting to specific part, outcomes or events and potentially contributing to further development of unintended consequences. Systems thinking is not one thing but a set of habits or practices [1] within a framework that is based on the belief that the component parts of a system can best be understood in the context of relationships with each other and with other systems, rather than in isolation. Systems thinking focuses on cyclical rather than linear cause and effect.

In science systems, it is argued that the only way to fully understand why a problem or element occurs and persists is to understand the parts in relation to the whole.[2] Standing in contrast to Descartes's scientific reductionism and philosophical analysis, it proposes to view systems in a holistic manner. Consistent with systems philosophy, systems thinking concerns an understanding of a system by examining the linkages and interactions between the elements that compose the entirety of the system.

Science systems thinking attempts to illustrate that events are separated by distance and time and that small catalytic events can cause large changes in complex systems. Acknowledging that an improvement in one area of a system can adversely affect another area of the system, it promotes organizational communication at all levels in order to avoid the silo effect. Systems thinking techniques may be used to study any kind of system — natural, scientific, engineered, human, or conceptual.

The concept of a system

Science systems thinkers consider that:

- a system is a dynamic and complex whole, interacting as a structured functional unit;
- energy, material and information flow among the different elements that compose the system;
- a system is a community situated within an environment;
- energy, material and information flow from and to the surrounding environment via semi-permeable membranes or boundaries;
- systems are often composed of entities seeking equilibrium but can exhibit oscillating, chaotic, or exponential behavior.

A holistic system is any set (group) of interdependent or temporally interacting parts. *Parts* are generally systems themselves and are composed of other parts, just as systems are generally parts or *holons* of other systems.

Science systems and the application of science systems thinking has been grouped into three categories based on the techniques used to tackle a system:

- Hard systems — involving simulations, often using computers and the techniques of operations research. Useful for problems that can justifiably be quantified. However it cannot easily take into account unquantifiable variables (opinions, culture, politics, etc), and may treat people as being passive, rather than having complex motivations.
- Soft systems — For systems that cannot easily be quantified, especially those involving people holding multiple and conflicting frames of reference. Useful for understanding motivations, viewpoints, and interactions and addressing qualitative as well as quantitative dimensions of problem situations. Soft systems are a field that utilizes foundation methodological work developed by Peter Checkland, Brian Wilson and their colleagues at

Lancaster University. Morphological analysis is a complementary method for structuring and analysing non-quantifiable problem complexes.

- Evolutionary systems — Béla H. Bánáthy developed a methodology that is applicable to the design of complex social systems. This technique integrates critical systems inquiry with soft systems methodologies. Evolutionary systems, similar to dynamic systems are understood as open, complex systems, but with the capacity to evolve over time. Bánáthy uniquely integrated the interdisciplinary perspectives of systems research (including chaos, complexity, cybernetics), cultural anthropology, evolutionary theory, and others.

The systems approach

The systems thinking approach incorporates several tenets:[3]

- Interdependence of objects and their attributes - independent elements can never constitute a system
- Holism - emergent properties not possible to detect by analysis should be possible to define by a holistic approach
- Goal seeking - systemic interaction must result in some goal or final state
- Inputs and Outputs - in a closed system inputs are determined once and constant; in an open system additional inputs are admitted from the environment
- Transformation of inputs into outputs - this is the process by which the goals are obtained
- Entropy - the amount of disorder or randomness present in any system
- Regulation - a method of feedback is necessary for the system to operate predictably
- Hierarchy - complex wholes are made up of smaller subsystems
- Differentiation - specialized units perform specialized functions
- Equifinality - alternative ways of attaining the same objectives (convergence)
- Multifinality - attaining alternative objectives from the same inputs (divergence)

Some examples:

- Rather than trying to improve the braking system on a car by looking in great detail at the material composition of the brake pads (reductionist), the *boundary* of the braking system may be extended to include the interactions between the:
  - brake disks or drums
  - brake pedal sensors
  - hydraulics
  - driver reaction time
  - tires
  - road conditions
  - weather conditions
  - time of day
- Using the tenet of "Multifinality", a supermarket could be considered to be:
  - a "profit making system" from the perspective of management and owners
  - a "distribution system" from the perspective of the suppliers
  - an "employment system" from the perspective of employees
  - a "materials supply system" from the perspective of customers
  - an "entertainment system" from the perspective of loiterers
  - a "social system" from the perspective of local residents
  - a "dating system" from the perspective of single customers

As a result of such thinking, new insights may be gained into how the supermarket works, why it has problems, how it can be improved or how changes made to one component of the system may impact the other components.

Applications

Science systems thinking is increasingly being used to tackle a wide variety of subjects in fields such as computing, engineering, epidemiology, information science, health, manufacture, management, and the environment.

Some examples:

- Organizational architecture
- Job design
- Team Population and Work Unit Design
- Linear and Complex Process Design
- Supply Chain Design
- Business continuity planning with FMEA protocol
- Critical Infrastructure Protection via FBI Infragard
- Delphi method — developed by RAND for USAF
- Futures studies — Thought leadership mentoring
- The public sector including examples at The Systems Thinking Review [4]
- Leadership development
- Oceanography — forecasting complex systems behavior
- Permaculture
- Quality function deployment (QFD)
- Quality management — Hoshin planning [5] methods
- Quality storyboard — StoryTech framework (LeapfrogU-EE)
- Software quality
- Program management
- Project management
- MECE - McKinsey Way

See also

- Boundary critique
- Crossdisciplinarity
- Holistic management
- Information Flow Diagram
- Interdisciplinary
- Multidisciplinary
- Negative feedback
- Soft systems methodology
- Synergetics (Fuller)
- System dynamics
- Systematics - study of multi-term systems
- Systemics
- Systems engineering
- Systems intelligence
- Systems philosophy
- Systems theory
- Systems science
- Transdisciplinary
- Terms used in systems theory

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- Brian Wilson (2001) *Soft Systems Methodology: Conceptual Model Building and its Contribution*. (Wiley) ISBN 0-471-89489-3

External links

- International Society for the Systems Sciences (ISSS) on Wikipedia,
- International Society for the System Sciences home page [8]
- UK Systems Society [9]
- The Systems Thinker newsletter glossary [10]
- Dancing With Systems [11] from Project Worldview
- Systems-thinking.de [12]: systems thinking links displayed as a network
- Systems Thinking [13]

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[4] http://www.thesystemsthinkingreview.co.uk/
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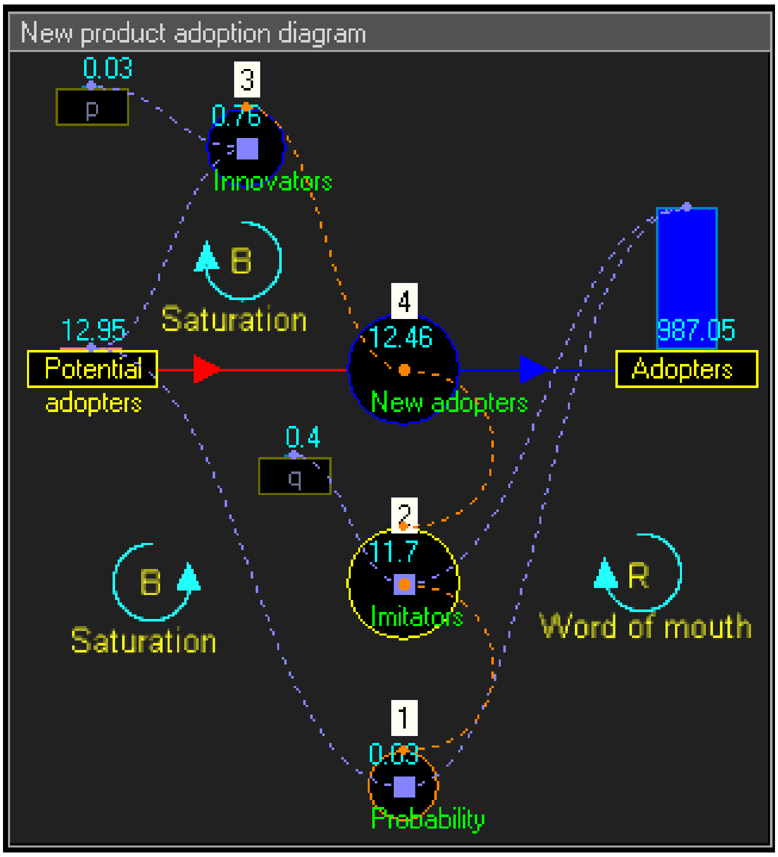
[6] http://triarchypress.com/pages/Systems_Thinking_for_Curious_Managers.htm
[7] http://www.triarchypress.co.uk/pages/book5.htm
[8] http://isss.org/world/
[9] http://www.ukss.org.uk
[10] http://www.thesystemsthinker.com/systemsthinkinglearn.html
[11] http://www.projectworldview.org/wvtheme13.htm
[12] http://www.systems-thinking.de/
[13] http://www.thinking.net/Systems_Thinking/systems_thinking.html

System dynamics



Dynamic stock and flow diagram of model *New product adoption* (model from article by John Sterman 2001)

System dynamics is an approach to understanding the behaviour of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of the entire system.[1] What makes using system dynamics different from other approaches to studying complex systems is the use of feedback loops and stocks and flows. These elements help describe how even seemingly simple systems display baffling nonlinearity.

Overview

System dynamics is a methodology and computer simulation modeling technique for framing, understanding, and discussing complex issues and problems. Originally developed in the 1950s to help corporate managers improve their understanding of industrial processes, system dynamics is currently being used throughout the public and private sector for policy analysis and design.[2]

System dynamics is an aspect of systems theory as a method for understanding the dynamic behavior of complex systems. The basis of the method is the recognition that the structure of any system — the many circular, interlocking, sometimes time-delayed relationships among its components — is often just as important in determining its behavior as the individual components themselves. Examples are chaos theory and social dynamics. It is also claimed that because there are often properties-of-the-whole which cannot be found among the properties-of-the-elements, in some cases the behavior of the whole cannot be explained in terms of the behavior of the parts.

History

System dynamics was created during the mid-1950s by Professor Jay Forrester of the Massachusetts Institute of Technology. In 1956, Forrester accepted a professorship in the newly-formed MIT School of Management. His initial goal was to determine how his background in science and engineering could be brought to bear, in some useful way, on the core issues that determine the success or failure of corporations. Forrester's insights into the common foundations that underlie engineering and management, which led to the creation of system dynamics, were triggered, to a large degree, by his involvement with managers at General Electric (GE) during the mid-1950s. At that time, the managers at GE were perplexed because employment at their appliance plants in Kentucky exhibited a significant three-year cycle. The business cycle was judged to be an insufficient explanation for the employment

instability. From hand simulations (or calculations) of the stock-flow-feedback structure of the GE plants, which included the existing corporate decision-making structure for hiring and layoffs, Forrester was able to show how the instability in GE employment was due to the internal structure of the firm and not to an external force such as the business cycle. These hand simulations were the beginning of the field of system dynamics.[2]

During the late 1950s and early 1960s, Forrester and a team of graduate students moved the emerging field of system dynamics from the hand-simulation stage to the formal computer modeling stage. Richard Bennett created the first system dynamics computer modeling language called SIMPLE (Simulation of Industrial Management Problems with Lots of Equations) in the spring of 1958. In 1959, Phyllis Fox and Alexander Pugh wrote the first version of DYNAMO (DYNAmic MOdels), an improved version of SIMPLE, and the system dynamics language became the industry standard for over thirty years. Forrester published the first, and still classic, book in the field titled Industrial Dynamics in 1961.[2]

From the late 1950s to the late 1960s, system dynamics was applied almost exclusively to corporate/managerial problems. In 1968, however, an unexpected occurrence caused the field to broaden beyond corporate modeling. John Collins, the former mayor of Boston, was appointed a visiting professor of Urban Affairs at MIT. The result of the Collins-Forrester collaboration was a book titled Urban Dynamics. The Urban Dynamics model presented in the book was the first major non-corporate application of system dynamics.[2]

The second major noncorporate application of system dynamics came shortly after the first. In 1970, Jay Forrester was invited by the Club of Rome to a meeting in Bern, Switzerland. The Club of Rome is an organization devoted to solving what its members describe as the "predicament of mankind" -- that is, the global crisis that may appear sometime in the future, due to the demands being placed on the earth's carrying capacity (its sources of renewable and nonrenewable resources and its sinks for the disposal of pollutants) by the world's exponentially growing population. At the Bern meeting, Forrester was asked if system dynamics could be used to address the predicament of mankind. His answer, of course, was that it could. On the plane back from the Bern meeting, Forrester created the first draft of a system dynamics model of the world's socioeconomic system. He called this model WORLD1. Upon his return to the United States, Forrester refined WORLD1 in preparation for a visit to MIT by members of the Club of Rome. Forrester called the refined version of the model WORLD2. Forrester published WORLD2 in a book titled World Dynamics.[2]

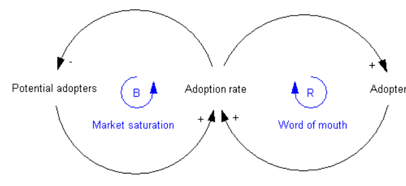
Topics in systems dynamics

The elements of system dynamics diagrams are feedback, accumulation of flows into stocks and time delays.

As an illustration of the use of system dynamics, imagine an organisation that plans to introduce an innovative new durable consumer product. The organisation needs to understand the possible market dynamics in order to design marketing and production plans.

Causal loop diagrams

A causal loop diagram is a visual representation of the feedback loops in a system. The causal loop diagram of the new product introduction may look as follows:

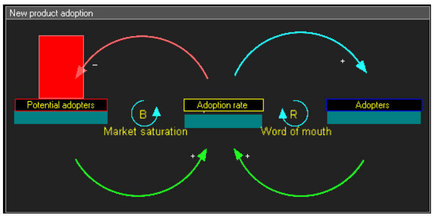


Causal loop diagram of *New product adoption* model

There are two feedback loops in this diagram. The positive reinforcement (labeled R) loop on the right indicates that the more people have already adopted the new product, the stronger the word-of-mouth impact. There will be more references to the product, more demonstrations, and more reviews. This positive feedback should generate sales that continue to grow.

The second feedback loop on the left is negative reinforcement (or "balancing" and hence labeled B). Clearly growth can not continue forever, because as more and more people adopt, there remain fewer and fewer potential adopters.

Both feedback loops act simultaneously, but at different times they may have different strengths. Thus one would expect growing sales in the initial years, and then declining sales in the later years.



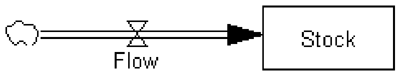
Causal loop diagram of *New product adoption* model with nodes values after calculus

In this dynamic causal loop diagram :

- step1 : (+) green arrows show that *Adoption rate* is function of *Potential Adopters* and *Adopters*
- step2 : (-) red arrow shows that *Potential adopters* decreases by *Adoption rate*
- step3 : (+) blue arrow shows that *Adopters* increases by *Adoption rate*

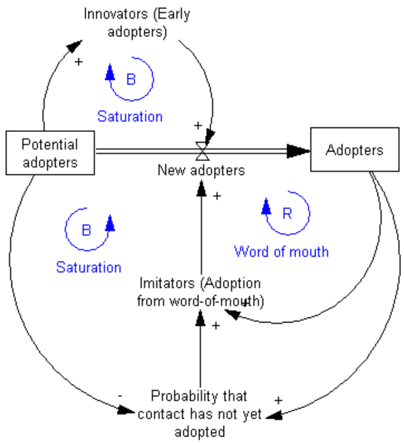
Stock and flow diagrams

The next step is to create what is termed a stock and flow diagram. A stock is the term for any entity that accumulates or depletes over time. A flow is the rate of change in a stock.



A flow changes the rate of accumulation of the stock

In our example, there are two stocks: Potential adopters and Adopters. There is one flow: New adopters. For every new adopter, the stock of potential adopters declines by one, and the stock of adopters increases by one.



Stock and flow diagram of *New product adoption* model

Equations

The real power of system dynamics is utilised through simulation. Although it is possible to perform the modeling in a spreadsheet, there are a variety of software packages that have been optimised for this.

The steps involved in a simulation are:

- Define the problem boundary
- Identify the most important stocks and flows that change these stock levels
- Identify sources of information that impact the flows
- Identify the main feedback loops
- Draw a causal loop diagram that links the stocks, flows and sources of information
- Write the equations that determine the flows
- Estimate the parameters and initial conditions. These can be estimated using statistical methods, expert opinion, market research data or other relevant sources of information.[3]
- Simulate the model and analyse results

In this example, the equations that change the two stocks via the flow are:

$$\text{Potential adopters} = \int_0^t \text{-New adopters } \,dt$$

$$\text{Adopters} = \int_0^t \text{New adopters } \,dt$$

List of all the equations, in their order of execution in each year, from year 1 to 15:

$$1)\ \text{Probability that contact has not yet adopted} = \frac{\text{Potential adopters}}{\text{Potential adopters } + \text{ Adopters}}$$

$$2)\ \text{Imitators} = q \cdot \text{Adopters} \cdot \text{Probability that contact has not yet adopted}$$

$$3)\ \text{Innovators} = p \cdot \text{Potential adopters}$$

$$4)\ \text{New adopters} = \text{Innovators} + \text{Imitators}$$

$$4.1)\ \text{Potential adopters } - = \text{New adopters}$$

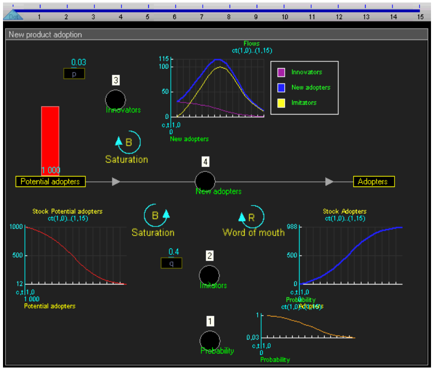
$$4.2)\ \text{Adopters } + = \text{New adopters}$$

$p = 0.03$

$q = 0.4$

Dynamic simulation results

The dynamic simulation results show that the behaviour of the system would be to have growth in **Adopters** that follows a classical s-curve shape.
The increase in **Adopters** is very slow initially, then exponential growth for a period, followed ultimately by saturation.



Dynamic stock and flow diagram of *New product adoption* model

Year	Probability	Imitators	Innovators	New adopters	Potential adopters	Adopters
0	0,00	0,00	0,00	0,00	1 000,00	0,00
1	1,00	0,00	30,00	30,00	970,00	30,00
2	0,97	11,64	29,10	40,74	929,26	70,74
3	0,93	26,32	27,88	54,20	875,06	124,94
4	0,88	43,98	26,25	70,23	804,83	195,17
5	0,80	62,45	24,14	86,59	718,24	281,76
6	0,72	81,15	21,55	102,70	615,54	384,46
7	0,62	95,35	18,47	113,82	501,72	498,28
8	0,50	99,66	15,05	114,71	387,01	612,99
9	0,39	95,63	11,61	107,24	279,77	720,23
10	0,28	80,67	8,39	89,06	190,71	809,29
11	0,19	61,51	5,72	67,23	123,48	876,52
12	0,12	42,07	3,70	45,77	77,71	922,29
13	0,08	29,51	2,33	31,84	45,87	954,13
14	0,05	19,08	1,38	20,46	25,41	974,59
15	0,03	11,70	0,76	12,46	12,95	987,05

Stocks and flows values for years = 0 to 15

Application

System dynamics has found application in a wide range of areas, for example population, ecological and economic systems, which usually interact strongly with each other.

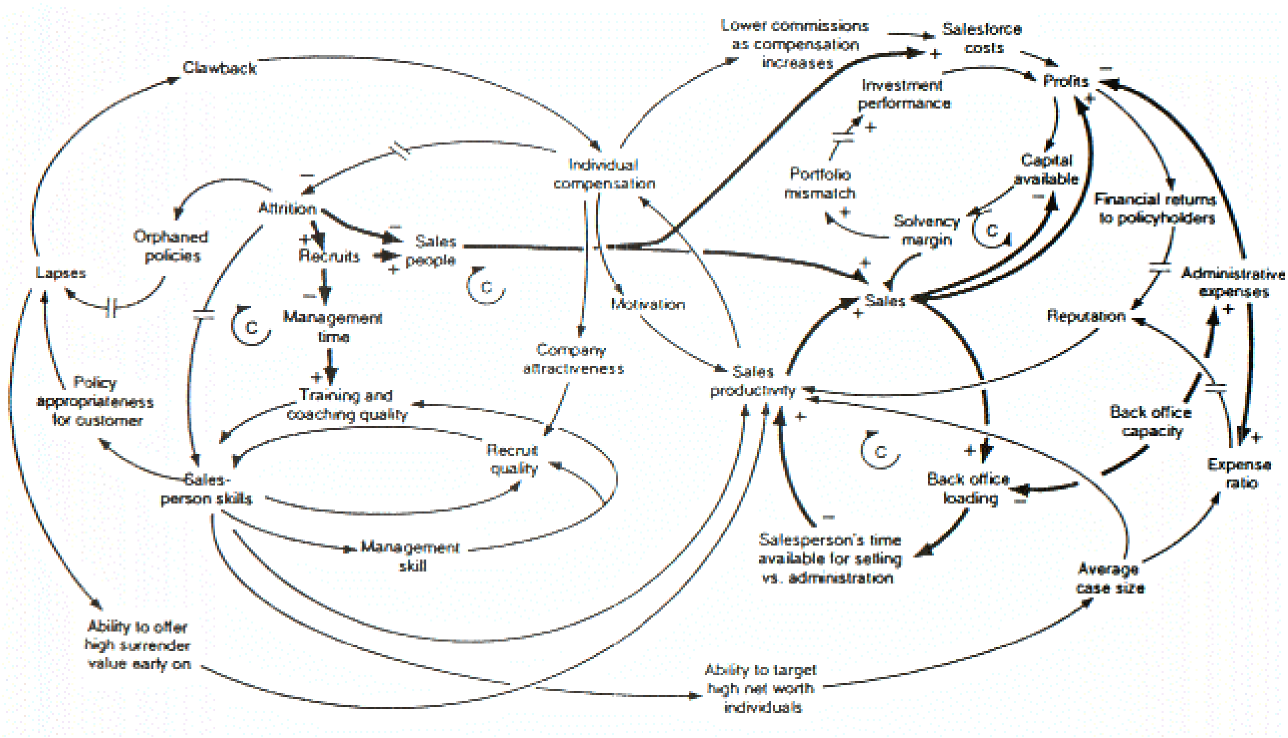
System dynamics have various "back of the envelope" management applications. They are a potent tool to:

- Teach system thinking reflexes to persons being coached
- Analyze and compare assumptions and mental models about the way things work
- Gain qualitative insight into the workings of a system or the consequences of a decision
- Recognize archetypes of dysfunctional systems in everyday practice

Computer software is used to simulate a system dynamics model of the situation being studied. Running "what if" simulations to test certain policies on such a model can greatly aid in understanding how the system changes over time. System dynamics is very similar to systems thinking and constructs the same causal loop diagrams of systems with feedback. However, system dynamics typically goes further and utilises simulation to study the behaviour of systems and the impact of alternative policies.[4]

System dynamics has been used to investigate resource dependencies, and resulting problems, in product development.[5] [6]

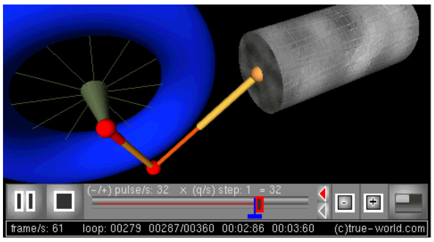
Example



Causal loop diagram of a model examining the growth or decline of a life insurance company.[7]

The figure above is a causal loop diagram of a system dynamics model created to examine forces that may be responsible for the growth or decline of life insurance companies in the United Kingdom. A number of this figure's features are worth mentioning. The first is that the model's negative feedback loops are identified by "C's," which stand for "Counteracting" loops. The second is that double slashes are used to indicate places where there is a significant delay between causes (i.e., variables at the tails of arrows) and effects (i.e., variables at the heads of arrows). This is a common causal loop diagramming convention in system dynamics. Third, is that thicker lines are used to identify the feedback loops and links that author wishes the audience to focus on. This is also a common system dynamics diagramming convention. Last, it is clear that a decision maker would find it impossible to think through the dynamic behavior inherent in the model, from inspection of the figure alone.[7]

Example of 4D piston motion



Piston_motion_equations

This animation was made with the 3D modeler of a system dynamics software.
The calculated values are associated with parameters of the rod and crank.
In this example the crank is driving, we vary both the speed of rotation, its radius and the length of the rod, the piston follows.

See also

Related subjects	Related fields	Related scientists
• Causal loop diagram • Ecosystem model • Plateau Principle • System Archetypes • System Dynamics Society • Twelve leverage points • Wicked problems • World3 • Population dynamics • Predator-prey interaction	• Dynamical systems theory • Operations research • Social dynamics • Systems theory • Systems thinking • TRIZ	• Jay Forrester • Dennis Meadows • Donella Meadows • Peter Senge • John Sterman

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External links

- U.S. Department of Energy's Introduction to System Dynamics [8]
- Desert Island Dynamics [9] "An Annotated Survey of the Essential System Dynamics Literature"

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Dynamics

Dynamics (from Greek *δυναμικός* - *dynamikos* "powerful", from *δύναμις* - *dynamis* "power") may refer to:

- Dynamics (music), In music, dynamics refers to the softness or loudness of a sound or note. The term is also applied to the written or printed musical notation used to indicate dynamics (also known as volume in a song)

GBF Underground Mining

Physics

- Dynamics (physics), in physics, dynamics refers to time evolution of physical processes

Field

- Analytical dynamics refers to the motion of bodies as induced by external forces
- Flight dynamics, the science of aircraft and spacecraft design
- Force Dynamics
- Fluid dynamics, the study of fluid flow
  - Computational fluid dynamics
- Molecular dynamics, the study of motion on the molecular level
  - Langevin dynamics
    - Brownian dynamics
- In quantum physics, *dynamics* may refer to how forces are quantized, as in quantum electrodynamics or quantum chromodynamics
- Relativistic dynamics may refer to a combination of relativistic and quantum concepts
- Stellar dynamics
- System dynamics, the study of the behaviour of complex systems
- Thermodynamics, a branch of physics that studies the relationships between heat and mechanical energy

Branch

- Aerodynamics, the study of gases in motion
- Hydrodynamics, the study of liquids or water in motion
- Neurodynamics, an area of research in the brain sciences which places a strong focus upon the spatio-temporal (dynamic) character of neural activity in describing brain function
- Thermodynamics

Sociology

- Group dynamics, the study of social group processes
- Population dynamics
- Power dynamics, the dynamics of power, used in sociology
- Psychodynamics, the study of the interrelationship of various parts of the mind, personality, or psyche as they relate to mental, emotional, or motivational forces especially at the subconscious level
- Spiral Dynamics, a social development theory
- Social dynamics (interdisciplinary)

Computer science and math

- Dynamical system, in mathematics or complexity
- Dynamic programming in computer science and control theory
- Dynamic program analysis, in computer science, a set of methods for analyzing code that is performed with executing programs built from that software on a real or virtual processor
- Symbolic dynamics

Companies

- Arrow Dynamics, rollercoast company
- Boston Dynamics, robot design company
- Crystal Dynamics, video game developer
- General Dynamics

Other

- Microsoft Dynamics, a line of business software owned and developed by Microsoft

See also

- All pages beginning with "dynamic"
- All pages with titles containing "dynamic"
- Power (disambiguation)
- Kinetics (disambiguation)
- Dynamic Host Configuration Protocol

Mathematical Biology, Complex Systems Biology

Mathematical biology

Mathematical and theoretical biology is an interdisciplinary academic research field with a range of applications in biology, medicine and biotechnology.[1] The field may be referred to as **mathematical biology** or **biomathematics** to stress the mathematical side, or as **theoretical biology** to stress the biological side.[2] It includes at least four major subfields: *biological mathematical modeling*, *relational biology/complex systems biology (CSB)*, *bioinformatics* and *computational biomodeling/biocomputing*.

Mathematical biology aims at the mathematical representation, treatment and modeling of biological processes, using a variety of applied mathematical techniques and tools. It has both theoretical and practical applications in biological, biomedical and biotechnology research. For example, in cell biology, protein interactions are often represented as "cartoon" models, which, although easy to visualize, do not accurately describe the systems studied. In order to do this, precise mathematical models are required. By describing the systems in a quantitative manner, their behavior can be better simulated, and hence properties can be predicted that might not be evident to the experimenter.

Importance

Applying mathematics to biology has a long history, but only recently has there been an explosion of interest in the field. Some reasons for this include:

- the explosion of data-rich information sets, due to the genomics revolution, which are difficult to understand without the use of analytical tools,
- recent development of mathematical tools such as chaos theory to help understand complex, nonlinear mechanisms in biology,
- an increase in computing power which enables calculations and simulations to be performed that were not previously possible, and
- an increasing interest in in silico experimentation due to ethical considerations, risk, unreliability and other complications involved in human and animal research.

Areas of research

Several areas of specialized research in mathematical and theoretical biology[3] [4] [5] [6] [7] as well as external links to related projects in various universities are concisely presented in the following subsections, including also a large number of appropriate validating references from a list of several thousands of published authors contributing to this field. Many of the included examples are characterised by highly complex, nonlinear, and supercomplex mechanisms, as it is being increasingly recognised that the result of such interactions may only be understood through a combination of mathematical, logical, physical/chemical, molecular and computational models. Due to the wide diversity of specific knowledge involved, biomathematical research is often done in collaboration between mathematicians, biomathematicians, theoretical biologists, physicists, biophysicists, biochemists, bioengineers, engineers, biologists, physiologists, research physicians, biomedical researchers, oncologists, molecular biologists, geneticists, embryologists, zoologists, chemists, etc.

Computer models and automata theory

A monograph on this topic summarizes an extensive amount of published research in this area up to 1987,[8] including subsections in the following areas: computer modeling in biology and medicine, arterial system models, neuron models, biochemical and oscillation networks, quantum automata [9], quantum computers in molecular biology and genetics, cancer modelling, neural nets, genetic networks, abstract relational biology, metabolic-replication systems, category theory[10] applications in biology and medicine,[11] automata theory, cellular automata, tessallation models[12] [13] and complete self-reproduction [14], chaotic systems in organisms, relational biology and organismic theories.[15] [16] This published report also includes 390 references to peer-reviewed articles by a large number of authors.[3] [17] [18]

Modeling cell and molecular biology

This area has received a boost due to the growing importance of molecular biology.[6]

- Mechanics of biological tissues[19]
- Theoretical enzymology and enzyme kinetics
- Cancer modelling and simulation[20] [21]
- Modelling the movement of interacting cell populations[22]
- Mathematical modelling of scar tissue formation[23]
- Mathematical modelling of intracellular dynamics[24]
- Mathematical modelling of the cell cycle[25]

Modelling physiological systems

- Modelling of arterial disease [26]
- Multi-scale modelling of the heart [27]

Molecular set theory

Molecular set theory was introduced by Anthony Bartholomay, and its applications were developed in mathematical biology and especially in Mathematical Medicine.[28] Molecular set theory (MST) is a mathematical formulation of the wide-sense chemical kinetics of biomolecular reactions in terms of sets of molecules and their chemical transformations represented by set-theoretical mappings between molecular sets. In a more general sense, MST is the theory of molecular categories defined as categories of molecular sets and their chemical transformations represented as set-theoretical mappings of molecular sets. The theory has also contributed to biostatistics and the formulation of clinical biochemistry problems in mathematical formulations of pathological, biochemical changes of interest to Physiology, Clinical Biochemistry and Medicine.[28] [29]

Population dynamics

Population dynamics has traditionally been the dominant field of mathematical biology. Work in this area dates back to the 19th century. The Lotka–Volterra predator-prey equations are a famous example. In the past 30 years, population dynamics has been complemented by evolutionary game theory, developed first by John Maynard Smith. Under these dynamics, evolutionary biology concepts may take a deterministic mathematical form. Population dynamics overlap with another active area of research in mathematical biology: mathematical epidemiology, the study of infectious disease affecting populations. Various models of the spread of infections have been proposed and analyzed, and provide important results that may be applied to health policy decisions.

Mathematical methods

A model of a biological system is converted into a system of equations, although the word 'model' is often used synonymously with the system of corresponding equations. The solution of the equations, by either analytical or numerical means, describes how the biological system behaves either over time or at equilibrium. There are many different types of equations and the type of behavior that can occur is dependent on both the model and the equations used. The model often makes assumptions about the system. The equations may also make assumptions about the nature of what may occur.

Mathematical biophysics

The earlier stages of mathematical biology were dominated by mathematical biophysics, described as the application of mathematics in biophysics, often involving specific physical/mathematical models of biosystems and their components or compartments.

The following is a list of mathematical descriptions and their assumptions.

Deterministic processes (dynamical systems)

A fixed mapping between an initial state and a final state. Starting from an initial condition and moving forward in time, a deterministic process will always generate the same trajectory and no two trajectories cross in state space.

- Difference equations/Maps – discrete time, continuous state space.
- Ordinary differential equations – continuous time, continuous state space, no spatial derivatives. *See also:* Numerical ordinary differential equations.
- Partial differential equations – continuous time, continuous state space, spatial derivatives. *See also:* Numerical partial differential equations.

Stochastic processes (random dynamical systems)

A random mapping between an initial state and a final state, making the state of the system a random variable with a corresponding probability distribution.

- Non-Markovian processes – generalized master equation – continuous time with memory of past events, discrete state space, waiting times of events (or transitions between states) discretely occur and have a generalized probability distribution.
- Jump Markov process – master equation – continuous time with no memory of past events, discrete state space, waiting times between events discretely occur and are exponentially distributed. *See also:* Monte Carlo method for numerical simulation methods, specifically continuous-time Monte Carlo which is also called kinetic Monte Carlo or the stochastic simulation algorithm.
- Continuous Markov process – stochastic differential equations or a Fokker-Planck equation – continuous time, continuous state space, events occur continuously according to a random Wiener process.

Spatial modelling

One classic work in this area is Alan Turing's paper on morphogenesis entitled *The Chemical Basis of Morphogenesis*, published in 1952 in the Philosophical Transactions of the Royal Society.

- Travelling waves in a wound-healing assay[30]
- Swarming behaviour[31]
- A mechanochemical theory of morphogenesis[32]
- Biological pattern formation[33]
- Spatial distribution modeling using plot samples[34]

Phylogenetics

Phylogenetics is an area that deals with the reconstruction and analysis of phylogenetic (evolutionary) trees and networks based on inherited characteristics[35]

Model example: the cell cycle

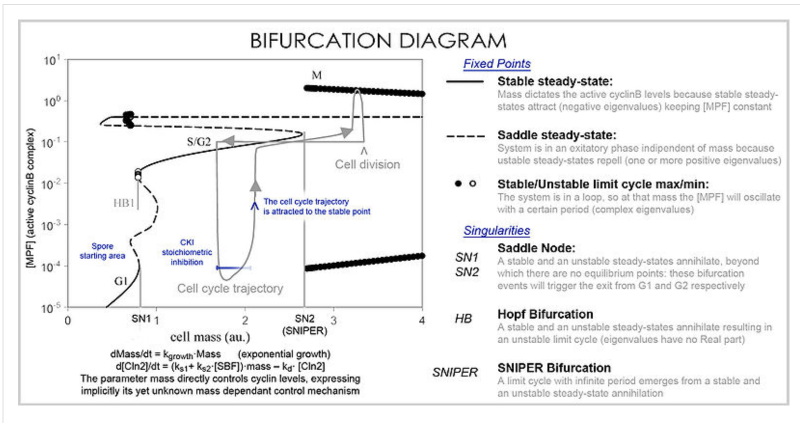
The eukaryotic cell cycle is very complex and is one of the most studied topics, since its misregulation leads to cancers. It is possibly a good example of a mathematical model as it deals with simple calculus but gives valid results. Two research groups [36] [37] have produced several models of the cell cycle simulating several organisms. They have recently produced a generic eukaryotic cell cycle model which can represent a particular eukaryote depending on the values of the parameters, demonstrating that the idiosyncrasies of the individual cell cycles are due to different protein concentrations and affinities, while the underlying mechanisms are conserved (Csikasz-Nagy et al., 2006).

By means of a system of ordinary differential equations these models show the change in time (dynamical system) of the protein inside a single typical cell; this type of model is called a deterministic process (whereas a model describing a statistical distribution of protein concentrations in a population of cells is called a stochastic process).

To obtain these equations an iterative series of steps must be done: first the several models and observations are combined to form a consensus diagram and the appropriate kinetic laws are chosen to write the differential equations, such as rate kinetics for stoichiometric reactions, Michaelis-Menten kinetics for enzyme substrate reactions and Goldbeter–Koshland kinetics for ultrasensitive transcription factors, afterwards the parameters of the equations (rate constants, enzyme efficiency coefficients and Michealis constants) must be fitted to match observations; when they cannot be fitted the kinetic equation is revised and when that is not possible the wiring diagram is modified. The parameters are fitted and validated using observations of both wild type and mutants, such as protein half-life and cell size.

In order to fit the parameters the differential equations need to be studied. This can be done either by simulation or by analysis.

In a simulation, given a starting vector (list of the values of the variables), the progression of the system is calculated by solving the equations at each time-frame in small increments.



In analysis, the proprieties of the equations are used to investigate the behavior of the system depending of the values of the parameters and variables. A system of differential equations can be represented as a vector field, where each vector described the change (in concentration of two or more protein) determining where and how fast the trajectory (simulation) is heading. Vector fields can have several special points: a stable point, called a sink, that attracts in all directions (forcing the concentrations to be at a certain value), an unstable point, either a source or a saddle point which repels (forcing the concentrations to change away from a certain value), and a limit cycle, a closed trajectory towards which several trajectories spiral towards (making the concentrations oscillate).

A better representation which can handle the large number of variables and parameters is called a bifurcation diagram(Bifurcation theory): the presence of these special steady-state points at certain values of a parameter (e.g. mass) is represented by a point and once the parameter passes a certain value, a qualitative change occurs, called a

bifurcation, in which the nature of the space changes, with profound consequences for the protein concentrations: the cell cycle has phases (partially corresponding to G1 and G2) in which mass, via a stable point, controls cyclin levels, and phases (S and M phases) in which the concentrations change independently, but once the phase has changed at a bifurcation event (Cell cycle checkpoint), the system cannot go back to the previous levels since at the current mass the vector field is profoundly different and the mass cannot be reversed back through the bifurcation event, making a checkpoint irreversible. In particular the S and M checkpoints are regulated by means of special bifurcations called a Hopf bifurcation and an infinite period bifurcation.

See also

- Abstract relational biology [38][39] [40]
- Artificial life
- Biocybernetics
- Bioinformatics
- Biologically inspired computing
- Biosemiotics
- Biostatistics
- Cellular automata[3]
- Coalescent theory
- Complex systems biology[41] [3] [42]
- Computational biology
- Digital morphogenesis
- Dynamical systems in biology[3] [42] [43] [44] [45] [46]
- Epidemiology
- Evolution theories and Population Genetics
    - Population genetics models
    - Molecular evolution theories
- Ewens's sampling formula
- Excitable medium
- Journal of Theoretical Biology
- Mathematical models
    - Molecular modelling
    - Molecular modelling on GPU
    - Software for molecular modeling
    - Metabolic-replication systems[47]
    - Models of Growth and Form
    - Neighbour-sensing model
- Morphometrics
- Organismic systems (OS) [48][49]
- Organismic supercategories [48][42] [50]
- Population dynamics of fisheries
- Protein folding, also blue Gene and folding@home
- Quantum computers
- Quantum genetics
- Relational biology[51]
- Self-reproduction[52] (also called self-replication in a more general context).
- Computational gene models

- Systems biology[53]
- Theoretical biology[54]
- Theoretical ecology
- Topological models of morphogenesis
  - DNA topology
  - DNA sequencing theory

  For use of basic arithmetics in biology, see relevant topic, such as Serial dilution.

- Biographies
  - Charles Darwin
  - D'Arcy Thompson
  - Joseph Fourier
  - Charles S. Peskin
  - Nicolas Rashevsky [55]
  - Robert Rosen
  - Rosalind Franklin
  - Francis Crick
  - René Thom
  - Vito Volterra

Societies and Institutes

- Division of Mathematical Biology at NIMR
- Society for Mathematical Biology
- European Society for Mathematical and Theoretical Biology

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External links

- The Society for Mathematical Biology [60]
- Theoretical and mathematical biology website [61]
- Complexity Discussion Group [62]
- UCLA Biocybernetics Laboratory [63]
- TUCS Computational Biomodelling Laboratory [64]
- Nagoya University Division of Biomodeling [65]
- Technische Universiteit Biomodeling and Informatics [66]
- BioCybernetics Wiki, a vertical wiki on biomedical cybernetics and systems biology [67]
- Bulletin of Mathematical Biology [68]
- European Society for Mathematical and Theoretical Biology [69]
- Journal of Mathematical Biology [70]
- Biomathematics Research Centre at University of Canterbury [71]
- Centre for Mathematical Biology at Oxford University [72]
- Mathematical Biology at the National Institute for Medical Research [73]
- Institute for Medical BioMathematics [74]
- *Mathematical Biology Systems of Differential Equations* [75] from EqWorld: The World of Mathematical Equations
- Systems Biology Workbench - a set of tools for modelling biochemical networks [76]
- The Collection of Biostatistics Research Archive [77]
- Statistical Applications in Genetics and Molecular Biology [78]
- The International Journal of Biostatistics [79]
- Theoretical Modeling of Cellular Physiology at Ecole Normale Superieure, Paris [80]

Lists of references

- A general list of Theoretical biology/Mathematical biology references, including an updated list of actively contributing authors [61].
- A list of references for applications of category theory in relational biology [81].
- An updated list of publications of theoretical biologist Robert Rosen [82]
- Theory of Biological Anthropology (Documents No. 9 and 10 in English) [83]
- Drawing the Line Between Theoretical and Basic Biology (a forum article by Isidro T. Savillo) [84]

Related journals

- Acta Biotheoretica [85]
- Bioinformatics [86]
- Biological Theory [87]
- BioSystems [88]
- Bulletin of Mathematical Biology [68]
- Ecological Modelling [89]
- Journal of Mathematical Biology [70]
- Journal of Theoretical Biology [90]
- Journal of the Royal Society Interface [91]
- Mathematical Biosciences [92]
- Medical Hypotheses [93]
- Rivista di Biologia-Biology Forum [94]
- Theoretical and Applied Genetics [95]
- Theoretical Biology and Medical Modelling [96]

- Theoretical Population Biology [97]
- Theory in Biosciences [98] (formerly: Biologisches Zentralblatt)

Related societies

- ESMTB: European Society for Mathematical and Theoretical Biology [69]
- The Israeli Society for Theoretical and Mathematical Biology [99]
- Société Francophone de Biologie Théorique [100]
- International Society for Biosemiotic Studies [101]

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Dynamical systems theory

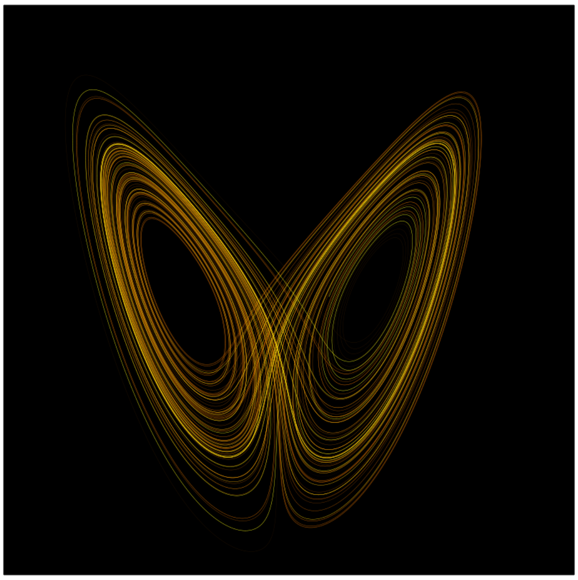
Dynamical systems theory is an area of applied mathematics used to describe the behavior of complex dynamical systems, usually by employing differential equations or difference equations. When differential equations are employed, the theory is called *continuous dynamical systems*. When difference equations are employed, the theory is called *discrete dynamical systems*. When the time variable runs over a set which is discrete over some intervals and continuous over other intervals or is any arbitrary time-set such as a cantor set then one gets dynamic equations on time scales. Some situations may also be modelled by mixed operators such as differential-difference equations.

This theory deals with the long-term qualitative behavior of dynamical systems, and the studies of the solutions to the equations of motion of systems that are primarily mechanical in nature; although this includes both planetary orbits as well as the behaviour of electronic circuits and the solutions to partial differential equations that arise in biology. Much of modern research is focused on the study of chaotic systems.

This field of study is also called just *Dynamical systems*, *Systems theory* or longer as *Mathematical Dynamical Systems Theory* and the *Mathematical theory of dynamical systems*.

Overview

Dynamical systems theory and chaos theory deal with the long-term qualitative behavior of dynamical systems. Here, the focus is not on finding precise solutions to the equations defining the dynamical system (which is often hopeless), but rather to answer questions like "Will the system settle down to a steady state in the long term, and if so, what are the possible steady states?", or "Does the long-term behavior of the system depend on its initial condition?"



The Lorenz attractor is an example of a non-linear dynamical system. Studying this system helped give rise to Chaos theory.

An important goal is to describe the fixed points, or steady states of a given dynamical system; these are values of the variable which won't change over time. Some of these fixed points are *attractive*, meaning that if the system starts out in a nearby state, it will converge towards the fixed point.

Similarly, one is interested in *periodic points*, states of the system which repeat themselves after several timesteps. Periodic points can also be attractive. Sarkovskii's theorem is an interesting statement about the number of periodic points of a one-dimensional discrete dynamical system.

Even simple nonlinear dynamical systems often exhibit almost random, completely unpredictable behavior that has been called *chaos*. The branch of dynamical systems which deals with the clean definition and investigation of chaos is called chaos theory.

History

The concept of dynamical systems theory has its origins in Newtonian mechanics. There, as in other natural sciences and engineering disciplines, the evolution rule of dynamical systems is given implicitly by a relation that gives the state of the system only a short time into the future.

Before the advent of fast computing machines, solving a dynamical system required sophisticated mathematical techniques and could only be accomplished for a small class of dynamical systems.

Some excellent presentations of mathematical dynamic system theory include Beltrami (1987), Luenberger (1979), Padula and Arbib (1974), and Strogatz (1994).[1]

Concepts

Dynamical systems

The dynamical system concept is a mathematical formalization for any fixed "rule" which describes the time dependence of a point's position in its ambient space. Examples include the mathematical models that describe the swinging of a clock pendulum, the flow of water in a pipe, and the number of fish each spring in a lake.

A dynamical system has a *state* determined by a collection of real numbers, or more generally by a set of points in an appropriate *state space*. Small changes in the state of the system correspond to small changes in the numbers. The numbers are also the coordinates of a geometrical space—a manifold. The *evolution rule* of the dynamical system is a fixed rule that describes what future states follow from the current state. The rule is deterministic: for a given time interval only one future state follows from the current state.

Dynamicism

Dynamicism, also termed the *dynamic hypothesis* or the *dynamic hypothesis in cognitive science* or *dynamic cognition*, is a new approach in cognitive science exemplified by the work of philosopher Tim van Gelder. It argues that differential equations are more suited to modelling cognition than more traditional computer models.

Nonlinear system

In mathematics, a nonlinear system is a system which is not linear, i.e. a system which does not satisfy the superposition principle. Less technically, a nonlinear system is any problem where the variable(s) to be solved for cannot be written as a linear sum of independent components. A nonhomogenous system, which is linear apart from the presence of a function of the independent variables, is nonlinear according to a strict definition, but such systems are usually studied alongside linear systems, because they can be transformed to a linear system as long as a particular solution is known.

Related fields

Arithmetic dynamics

Arithmetic dynamics is a field that emerged in the 1990s that amalgamates two areas of mathematics, dynamical systems and number theory. Classically, discrete dynamics refers to the study of the iteration of self-maps of the complex plane or real line. Arithmetic dynamics is the study of the number-theoretic properties of integer, rational, p-adic, and/or algebraic points under repeated application of a polynomial or rational function.

Chaos theory

Chaos theory describes the behavior of certain dynamical systems – that is, systems whose state evolves with time – that may exhibit dynamics that are highly sensitive to initial conditions (popularly referred to as the butterfly effect). As a result of this sensitivity, which manifests itself as an exponential growth of perturbations in the initial conditions, the behavior of chaotic systems appears to be random. This happens even though these systems are deterministic, meaning that their future dynamics are fully defined by their initial conditions, with no random elements involved. This behavior is known as deterministic chaos, or simply *chaos*.

Complex systems

Complex systems is a scientific field, which studies the common properties of systems considered complex in nature, society and science. It is also called *complex systems theory*, *complexity science*, *study of complex systems* and/or *sciences of complexity*. The key problems of such systems are difficulties with their formal modeling and simulation. From such perspective, in different research contexts complex systems are defined on the base of their different attributes.

The study of complex systems is bringing new vitality to many areas of science where a more typical reductionist strategy has fallen short. *Complex systems* is therefore often used as a broad term encompassing a research approach to problems in many diverse disciplines including neurosciences, social sciences, meteorology, chemistry, physics, computer science, psychology, artificial life, evolutionary computation, economics, earthquake prediction, molecular biology and inquiries into the nature of living cells themselves.

Control theory

Control theory is an interdisciplinary branch of engineering and mathematics, that deals with influencing the behavior of dynamical systems.

Ergodic theory

Ergodic theory is a branch of mathematics that studies dynamical systems with an invariant measure and related problems. Its initial development was motivated by problems of statistical physics.

Functional analysis

Functional analysis is the branch of mathematics, and specifically of analysis, concerned with the study of vector spaces and operators acting upon them. It has its historical roots in the study of functional spaces, in particular transformations of functions, such as the Fourier transform, as well as in the study of differential and integral equations. This usage of the word *functional* goes back to the calculus of variations, implying a function whose argument is a function. Its use in general has been attributed to mathematician and physicist Vito Volterra and its founding is largely attributed to mathematician Stefan Banach.

Graph dynamical systems

The concept of graph dynamical systems (GDS) can be used to capture a wide range of processes taking place on graphs or networks. A major theme in the mathematical and computational analysis of GDS is to relate their structural properties (e.g. the network connectivity) and the global dynamics that result.

Projected dynamical systems

Projected dynamical systems is a mathematical theory investigating the behaviour of dynamical systems where solutions are restricted to a constraint set. The discipline shares connections to and applications with both the static world of optimization and equilibrium problems and the dynamical world of ordinary differential equations. A projected dynamical system is given by the flow to the projected differential equation.

Symbolic dynamics

Symbolic dynamics is the practice of modelling a topological or smooth dynamical system by a discrete space consisting of infinite sequences of abstract symbols, each of which corresponds to a state of the system, with the dynamics (evolution) given by the shift operator.

System dynamics

System dynamics is an approach to understanding the behaviour of complex systems over time. It deals with internal feedback loops and time delays that affect the behaviour of the entire system.[2] What makes using system dynamics different from other approaches to studying complex systems is the use of feedback loops and stocks and flows. These elements help describe how even seemingly simple systems display baffling nonlinearity.

Topological dynamics

Topological dynamics is a branch of the theory of dynamical systems in which qualitative, asymptotic properties of dynamical systems are studied from the viewpoint of general topology.

Applications

In biomechanics

In sports biomechanics, dynamical systems theory has emerged in the movement sciences as a viable framework for modeling athletic performance. From a dynamical systems perspective, the human movement system is a highly intricate network of co-dependent sub-systems (e.g. respiratory, circulatory, nervous, skeletomuscular, perceptual) that are composed of a large number of interacting components (e.g. blood cells, oxygen molecules, muscle tissue, metabolic enzymes, connective tissue and bone). In dynamical systems theory, movement patterns emerge through generic processes of self-organization found in physical and biological systems.[3]

In cognitive science

Dynamical system theory has been applied in the field of neuroscience and cognitive development, especially in the neo-Piagetian theories of cognitive development. It is the belief that cognitive development is best represented by physical theories rather than theories based on syntax and AI. It also believes that differential equations are the most appropriate tool for modeling human behavior. These equations are interpreted to represent an agent's cognitive trajectory through state space. In other words, dynamicists argue that psychology should be (or is) the description (via differential equations) of the cognitions and behaviors of an agent under certain environmental and internal pressures. The language of chaos theory is also frequently adopted.

In it, the learner's mind reaches a state of disequilibrium where old patterns have broken down. This is the phase transition of cognitive development. Self organization (the spontaneous creation of coherent forms) sets in as activity levels link to each other. Newly formed macroscopic and microscopic structures support each other, speeding up the process. These links form the structure of a new state of order in the mind through a process called *scalloping* (the repeated building up and collapsing of complex performance.) This new, novel state is progressive, discrete, idiosyncratic and unpredictable. [4]

Dynamic systems theory has recently been used to explain a long-unanswered problem in child development referred to as the A-not-B error.[5]

See also

Related subjects

- List of dynamical system topics
- Baker's map
- Dynamical system (definition)
- Embodied Embedded Cognition
- Gingerbreadman map
- Halo orbit
- List of types of systems theory
- Oscillation
- Postcognitivism
- Recurrent neural network
- Combinatorics and dynamical systems
- Synergetics

Related scientists

- People in systems and control
- Dmitri Anosov
- Vladimir Arnold
- Nikolay Bogolyubov
- Andrey Kolmogorov
- Nikolay Krylov
- Jürgen Moser
- Yakov G. Sinai
- Stephen Smale
- Hillel Furstenberg

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External links

- Dynamic Systems [6] Encyclopedia of Cognitive Science entry.
- Definition of dynamical system [7] in MathWorld.
- DSWeb [8] Dynamical Systems Magazine

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[8] http://www.dynamicalsystems.org/

Living systems

Living systems are open self-organizing systems that have the special characteristics of life and interact with their environment. This takes place by means of information and material-energy exchanges.

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External links

- Joanna Macy pH.D. [2] on Living systems

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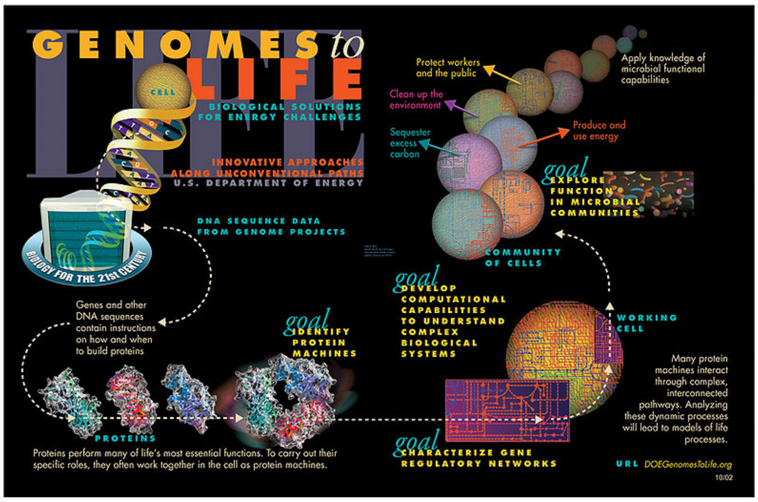
Complex Systems Biology (CSB)



Example of systems biology research.

Systems biology is a term used to describe a number of trends in bioscience research, and a movement which draws on those trends. Proponents describe systems biology as a biology-based inter-disciplinary study field that focuses on complex interactions in biological systems, claiming that it uses a new perspective (holism instead of reduction). Particularly from year 2000 onwards, the term is used widely in the biosciences, and in a variety of contexts. An often stated ambition of systems biology is the modeling and discovery of emergent properties, properties of a system whose theoretical description is only possible using techniques which fall under the remit of systems biology.

Overview

Systems biology can be considered from a number of different aspects:

- As a **field of study**, particularly, the study of the interactions between the components of *biological systems*, and how these interactions give rise to the function and behavior of that system (for example, the enzymes and metabolites in a metabolic pathway).[1] [2]
- As a **paradigm**, usually defined in antithesis to the so-called reductionist paradigm (biological organisation), although fully consistent with the scientific method. The distinction between the two paradigms is referred to in these quotations:

  "The reductionist approach has successfully identified most of the components and many of the interactions but, unfortunately, offers no convincing concepts or methods to understand how system properties emerge...the pluralism of causes and effects in biological networks is better addressed by observing, through quantitative measures, multiple components simultaneously and by rigorous data integration with mathematical models" Science[3]

  "Systems biology...is about putting together rather than taking apart, integration rather than reduction. It requires that we develop ways of thinking about integration that are as rigorous as our reductionist programmes, but different....It means changing our philosophy, in the full sense of the term" Denis Noble[4]
- As a series **operational protocols used for performing research**, namely a cycle composed of theory, analytic or computational modelling to propose specific testable hypotheses about a biological system, experimental validation, and then using the newly acquired quantitative description of cells or cell processes to refine the computational model or theory.[5] [6] Since the objective is a model of the interactions in a system, the experimental techniques that most suit systems biology are those that are system-wide and attempt to be as complete as possible. Therefore, transcriptomics, metabolomics, proteomics and high-throughput techniques are used to collect quantitative data for the construction and validation of models.
- As the application of dynamical systems theory to molecular biology.

- As a **socioscientific phenomenon** defined by the strategy of pursuing integration of complex data about the interactions in biological systems from diverse experimental sources using interdisciplinary tools and personnel.

This variety of viewpoints is illustrative of the fact that systems biology refers to a cluster of peripherally overlapping concepts rather than a single well-delineated field. However the term has widespread currency and popularity as of 2007, with chairs and institutes of systems biology proliferating worldwide.

History

Systems biology finds its roots in:

- the quantitative modeling of enzyme kinetics, a discipline that flourished between 1900 and 1970,
- the mathematical modeling of population growth,
- the simulations developed to study neurophysiology, and
- control theory and cybernetics.

One of the theorists who can be seen as one of the precursors of systems biology - and who allegedly coined the term in 1928 - is Ludwig von Bertalanffy with his general systems theory [7] . One of the first numerical simulations in biology was published in 1952 by the British neurophysiologists and Nobel prize winners Alan Lloyd Hodgkin and Andrew Fielding Huxley, who constructed a mathematical model that explained the action potential propagating along the axon of a neuronal cell.[8] Their model described a cellular function emerging from the interaction between two different molecular components, a potassium and a sodium channels, and can therefore be seen as the beginning of computational systems biology.[9] In 1960, Denis Noble developed the first computer model of the heart pacemaker.[10]

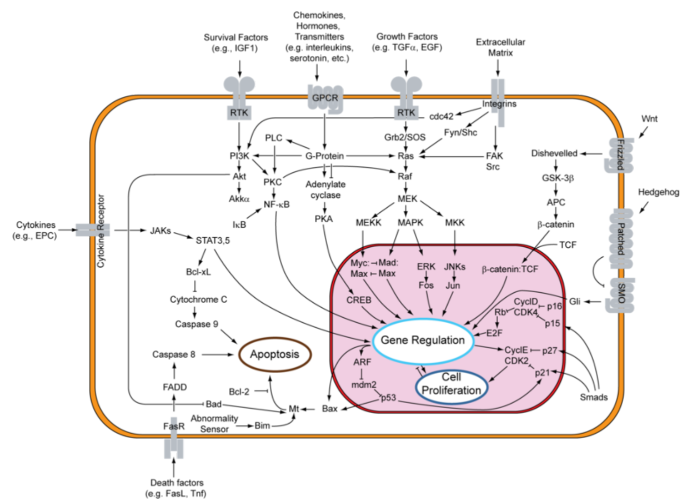
The formal study of systems biology, as a distinct discipline, was launched by systems theorist Mihajlo Mesarovic in 1966 with an international symposium at the Case Institute of Technology in Cleveland, Ohio entitled "Systems Theory and Biology."[11] [12]

The 1960s and 1970s saw the development of several approaches to study complex molecular systems, such as the Metabolic Control Analysis and the biochemical systems theory. The successes of molecular biology throughout the 1980s, coupled with a skepticism toward theoretical biology, that then promised more than it achieved, caused the quantitative modelling of biological processes to become a somewhat minor field.

However the birth of functional genomics in the 1990s meant that large quantities of high quality data became available, while the computing power exploded, making more realistic models possible. In 1997, the group of Masaru Tomita published the first quantitative model of the metabolism of a whole (hypothetical) cell.

Around the year 2000, after Institutes of Systems Biology were established in Seattle and Tokyo, systems biology emerged as a movement in its own right, spurred on by the completion of various genome projects, the large increase in data from the omics (e.g. genomics and proteomics) and the accompanying advances in high-throughput experiments and bioinformatics. Since then, various research institutes dedicated to systems biology have been developed. As of summer 2006, due to a shortage of people in systems biology[13] several doctoral training centres in systems biology have been established in many parts of the world.

Disciplines associated with systems biology



Overview of signal transduction pathways

According to the interpretation of System Biology as the ability to obtain, integrate and analyze complex data from multiple experimental sources using interdisciplinary tools, some typical technology platforms are:

- Genomics: Organismal deoxyribonucleic acid(DNA) sequence, including intra-organisamal cell specific variation. (i.e. Telomere length variation etc).
- Epigenomics / Epigenetics: Organismal and corresponding cell specific transcriptomic regulating factors not empirically coded in the genomic sequence. (i.e. DNA methylation, Histone Acetelation etc).
- Transcriptomics: Organismal, tissue or whole cell gene expression measurements by DNA microarrays or serial analysis of gene expression
- Interferomics: Organismal, tissue, or cell level transcript correcting factors (i.e. RNA interference)
- Translatomics / Proteomics: Organismal, tissue, or cell level measurements of proteins and peptides via two-dimensional gel electrophoresis, mass spectrometry or multi-dimensional protein identification techniques (advanced HPLC systems coupled with mass spectrometry). Sub disciplines include phosphoproteomics, glycoproteomics and other methods to detect chemically modified proteins.
- Metabolomics: Organismal, tissue, or cell level measurements of all small-molecules known as metabolites.
- Glycomics: Organismal, tissue, or cell level measurements of carbohydrates.
- Lipidomics: Organismal, tissue, or cell level measurements of lipids.

In addition to the identification and quantification of the above given molecules further techniques analyze the dynamics and interactions within a cell. This includes:

- Interactomics: Organismal, tissue, or cell level study of interactions between molecules. Currently the authoratative molecular discipline in this field of study is protein-protein interactions (PPI), although the working definition does not pre-clude inclusion of other molecular disciplines such as those defined here.
- Fluxomics: Organismal, tissue, or cell level measurements of molecular dynamic changes over time.
- Biomics: systems analysis of the biome.

The investigations are frequently combined with large scale perturbation methods, including gene-based (RNAi, mis-expression of wild type and mutant genes) and chemical approaches using small molecule libraries. Robots and automated sensors enable such large-scale experimentation and data acquisition. These technologies are still emerging and many face problems that the larger the quantity of data produced, the lower the quality. A wide variety of quantitative scientists (computational biologists, statisticians, mathematicians, computer scientists, engineers, and physicists) are working to improve the quality of these approaches and to create, refine, and retest the models to accurately reflect observations.

The systems biology approach often involves the development of mechanistic models, such as the reconstruction of dynamic systems from the quantitative properties of their elementary building blocks.[14] [15] For instance, a cellular network can be modelled mathematically using methods coming from chemical kinetics and control theory. Due to the large number of parameters, variables and constraints in cellular networks, numerical and computational techniques are often used. Other aspects of computer science and informatics are also used in systems biology. These include new forms of computational model, such as the use of process calculi to model biological processes, the

integration of information from the literature, using techniques of information extraction and text mining, the development of online databases and repositories for sharing data and models, approaches to database integration and software interoperability via loose coupling of software, websites and databases, or commercial suits, and the development of syntactically and semantically sound ways of representing biological models.

See also

Related fields

- Complex systems
- Complex systems biology
- Bioinformatics
- Biological network inference
- Biological systems engineering
- Biomedical cybernetics
- Biostatistics
- Extrapolation based molecular systems biology
- Theoretical Biophysics
- Relational Biology
- Translational Research
- Computational biology
- Computational systems biology
- Scotobiology
- Synthetic biology
- Systems biology modeling
- Systems ecology
- Systems immunology

Related terms

- Life
- Biological organisation
- Artificial life
- Gene regulatory network
- Metabolic network modelling
- Living systems theory
- Network Theory of Aging
- Regulome
- Systems Biology Markup Language (SBML)
- Systems Biology Graphical Notation (SBGN)
- SBO
- Viable System Model
- Antireductionism

Systems biologists

- Category:Systems biologists

Lists

- Category:Systems biologists
- List of systems biology conferences
- List of omics topics in biology
- List of publications in systems biology
- List of systems biology research groups
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- SystemsX.ch [49] - The Swiss Initiative in Systems Biology
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Network theory

For the anthropological theory, see Social network

Network theory is an area of computer science and network science and part of graph theory. It has application in many disciplines including particle physics, computer science, biology, economics, operations research, and sociology. Network theory concerns itself with the study of graphs as a representation of either symmetric relations or, more generally, of asymmetric relations between discrete objects. Applications of network theory include logistical networks, the World Wide Web, gene regulatory networks, metabolic networks, social networks, epistemological networks, etc. See list of network theory topics for more examples.

Network optimization

Network problems that involve finding an optimal way of doing something are studied under the name of combinatorial optimization. Examples include network flow, shortest path problem, transport problem, transshipment problem, location problem, matching problem, assignment problem, packing problem, routing problem, Critical Path Analysis and PERT (Program Evaluation & Review Technique).

Network analysis

Social network analysis

Social network analysis maps relationships between individuals in social networks.[1] Such individuals are often persons, but may be groups (including cliques and cohesive blocks [2]), organizations, nation states, web sites, or citations between scholarly publications (scientometrics).

Network analysis, and its close cousin traffic analysis, has significant use in intelligence. By monitoring the communication patterns between the network nodes, its structure can be established. This can be used for uncovering insurgent networks of both hierarchical and leaderless nature.

Biological network analysis

With the recent explosion of publicly available high throughput biological data, the analysis of molecular networks has gained significant interest. The type of analysis in this content are closely related to social network analysis, but often focusing on local patterns in the network. For example network motifs are small subgraphs that are over-represented in the network. Activity motifs are similar over-represented patterns in the attributes of nodes and edges in the network that are over represented given the network structure.

Link analysis

Link analysis is a subset of network analysis, exploring associations between objects. An example may be examining the addresses of suspects and victims, the telephone numbers they have dialed and financial transactions that they have partaken in during a given timeframe, and the familial relationships between these subjects as a part of police investigation. Link analysis here provides the crucial relationships and associations between very many objects of different types that are not apparent from isolated pieces of information. Computer-assisted or fully automatic computer-based link analysis is increasingly employed by banks and insurance agencies in fraud detection, by telecommunication operators in telecommunication network analysis, by medical sector in epidemiology and pharmacology, in law enforcement investigations, by search engines for relevance rating (and conversely by the spammers for spamdexing and by business owners for search engine optimization), and everywhere else where relationships between many objects have to be analyzed.

Web link analysis

Several Web search ranking algorithms use link-based centrality metrics, including (in order of appearance) Marchiori's Hyper Search, Google's PageRank, Kleinberg's HITS algorithm, and the TrustRank algorithm. Link analysis is also conducted in information science and communication science in order to understand and extract information from the structure of collections of web pages. For example the analysis might be of the interlinking between politicians' web sites or blogs.

Centrality measures

Information about the relative importance of nodes and edges in a graph can be obtained through centrality measures, widely used in disciplines like sociology. For example, eigenvector centrality uses the eigenvectors of the adjacency matrix to determine nodes that tend to be frequently visited.

Spread of content in networks

Content in a complex network can spread via two major methods: conserved spread and non-conserved spread.[3] In conserved spread, the total amount of content that enters a complex network remains constant as it passes through. The model of conserved spread can best be represented by a pitcher containing a fixed amount of water being poured into a series of funnels connected by tubes . Here, the pitcher represents the original source and the water is the content being spread. The funnels and connecting tubing represent the nodes and the connections between nodes, respectively. As the water passes from one funnel into another, the water disappears instantly from the funnel that was previously exposed to the water. In non-conserved spread, the amount of content changes as it enters and passes through a complex network. The model of non-conserved spread can best be represented by a continuously running faucet running through a series of funnels connected by tubes . Here, the amount of water from the original source is infinite. Also, any funnels that have been exposed to the water continue to experience the water even as it passes into

successive funnels. The non-conserved model is the most suitable for explaining the transmission of most infectious diseases.

Related Applications

Clay Shirky on institutions vs. collaboration Dan Pink on the surprising science of motivation

See also

- Complex network
- Network science
- Network topology
- Small-world networks
- Social circles
- Scale-free networks
- Sequential dynamical systems

Implementations

- Orange, a free data mining software suite, module orngNetwork [4]
- Pajek [5], program for (large) network analysis and visualization

External links

- netwiki [6] Scientific wiki dedicated to network theory
- New Network Theory [7] International Conference on 'New Network Theory'
- Network Workbench [8]: A Large-Scale Network Analysis, Modeling and Visualization Toolkit
- Network analysis of computer networks [9]
- Network analysis of organizational networks [10]
- Network analysis of terrorist networks [11]
- Network analysis of a disease outbreak [12]
- Link Analysis: An Information Science Approach [13] (book)
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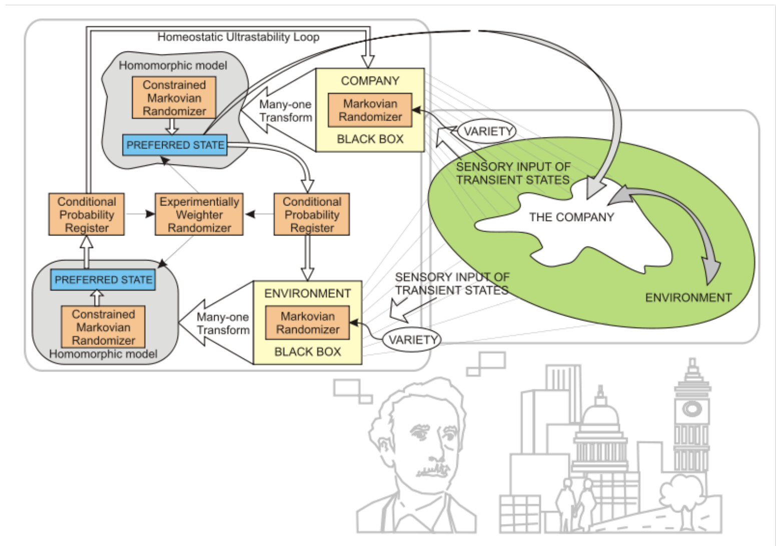
Cybernetics

Cybernetics is the interdisciplinary study of the structure of regulatory systems. Cybernetics is closely related to control theory and systems theory. Both in its origins and in its evolution in the second-half of the 20th century, cybernetics is equally applicable to physical and social (that is, language-based) systems.

Cybernetics is preeminent when the system under scrutiny is involved in a closed signal loop, where action by the system in an environment causes some change in the environment and that change is manifest to the system via information, or feedback, that causes the system to adapt to new conditions: the system changes its behavior. This "circular causal" relationship is necessary and sufficient for a cybernetic perspective. System Dynamics, a related field, originated with applications of electrical engineering control theory to other kinds of simulation models (especially business systems) by Jay Forrester at MIT in the 1950s. Convenient GUI system dynamics software developed into user friendly versions by the 1990s and have been applied to diverse systems. SD models solve the problem of simultaneity (mutual causation) by updating all variables in small time increments with positive and negative feedbacks and time delays structuring the interactions and control. The best known SD model is probably the 1972 The Limits to Growth. This model forecast that exponential growth would lead to economic collapse during the 21st century under a wide variety of growth scenarios.

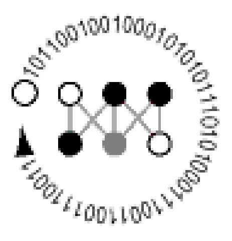


Example of cybernetic thinking. On the one hand a company is approached as a system in an environment. On the other hand cybernetic factory can be modeled as a control system.

Contemporary cybernetics began as an interdisciplinary study connecting the fields of control systems, electrical network theory, mechanical engineering, logic modeling, evolutionary biology, neuroscience, anthropology, and psychology in the 1940s, often attributed to the Macy Conferences.

Other fields of study which have influenced or been influenced by cybernetics include game theory, system theory (a mathematical counterpart to cybernetics), sociology, psychology (especially neuropsychology, behavioral psychology, cognitive psychology), philosophy, and architecture.[1]

Overview



The term *cybernetics* stems from the Greek κυβερνήτης (*kybernētēs*, steersman, governor, pilot, or rudder — the same root as government). Cybernetics is a broad field of study, but the essential goal of cybernetics is to understand and define the functions and processes of systems that have goals and that participate in circular, causal chains that move from action to sensing to comparison with desired goal, and again to action. Studies in cybernetics provide a means for examining the design and function of any system, including social systems such as business management and organizational learning, including for the purpose of making them more efficient and effective.

Cybernetics was defined by Norbert Wiener, in his book of that title, as the study of control and communication in the animal and the machine. Stafford Beer called it the science of effective organization and Gordon Pask extended it to include information flows "in all media" from stars to brains. It includes the study of feedback, black boxes and derived concepts such as communication and control in living organisms, machines and organizations including self-organization. Its focus is how anything (digital, mechanical or biological) processes information, reacts to information, and changes or can be changed to better accomplish the first two tasks [2] . A more philosophical definition, suggested in 1956 by Louis Couffignal, one of the pioneers of cybernetics, characterizes cybernetics as "the art of ensuring the efficacy of action" [3] . The most recent definition has been proposed by Louis Kauffman, President of the American Society for Cybernetics, "Cybernetics is the study of systems and processes that interact with themselves and produce themselves from themselves" [4] .

Concepts studied by cyberneticists (or, as some prefer, cyberneticians) include, but are not limited to: learning, cognition, adaption, social control, emergence, communication, efficiency, efficacy and interconnectivity. These concepts are studied by other subjects such as engineering and biology, but in cybernetics these are removed from the context of the individual organism or device.

Other fields of study which have influenced or been influenced by cybernetics include game theory; system theory (a mathematical counterpart to cybernetics); psychology, especially neuropsychology, behavioral psychology and cognitive psychology; philosophy; anthropology; and even architecture.

History

The roots of cybernetic theory

The word *cybernetics* was first used in the context of "the study of self-governance" by Plato in The Laws to signify the governance of people. The words govern and governor are related to the same Greek root through the Latin cognates gubernare and gubernator. The word "cybernétique" was also used in 1834 by the physicist André-Marie Ampère (1775–1836) to denote the sciences of government in his classification system of human knowledge.

The first artificial automatic regulatory system, a water clock, was invented by the mechanician Ktesibios. In his water clocks, water flowed from a source such as a holding tank into a reservoir, then from the reservoir to the mechanisms of the clock. Ktesibios's device used a cone-shaped float to monitor the level of the water in its reservoir and adjust the rate of flow of the water accordingly to maintain a constant level of water in the reservoir, so that it neither overflowed nor was allowed to run dry. This was the first artificial truly automatic self-regulatory device that required no outside intervention between the feedback and the controls of the mechanism. Although they did not refer to this concept by the name of Cybernetics (they considered it a field of engineering), Ktesibios and others such as Heron and Su Song are considered to be some of the first to study cybernetic principles.

James Watt

The study of *teleological mechanisms* (from the Greek τέλος or *telos* for *end*, *goal*, or *purpose*) in machines with *corrective feedback* dates from as far back as the late 1700s when James Watt's steam engine was equipped with a governor, a centrifugal feedback valve for controlling the speed of the engine. Alfred Russel Wallace identified this as the principle of evolution in his famous 1858 paper. In 1868 James Clerk Maxwell published a theoretical article on governors, one of the first to discuss and refine the principles of self-regulating devices. Jakob von Uexküll applied the feedback mechanism via his model of functional cycle (*Funktionskreis*) in order to explain animal behaviour and the origins of meaning in general.

The early 20th century

Contemporary cybernetics began as an interdisciplinary study connecting the fields of control systems, electrical network theory, mechanical engineering, logic modeling, evolutionary biology and neuroscience in the 1940s. Electronic control systems originated with the 1927 work of Bell Telephone Laboratories engineer Harold S. Black on using negative feedback to control amplifiers. The ideas are also related to the biological work of Ludwig von Bertalanffy in General Systems Theory.

Early applications of negative feedback in electronic circuits included the control of gun mounts and radar antenna during WWII. Jay Forrester, a graduate student at the Servomechanisms Laboratory at MIT during WWII working with Gordon S. Brown to develop electronic control systems for the U.S. Navy, later applied these ideas to social organizations such as corporations and cities as an original organizer of the MIT School of Industrial Management at the MIT Sloan School of Management. Forrester is known as the founder of System Dynamics.

W. Edwards Deming, the Total Quality Management guru for whom Japan named its top post-WWII industrial prize, was an intern at Bell Telephone Labs in 1927 and may have been influenced by network theory. Deming made "Understanding Systems" one of the four pillars of what he described as "Profound Knowledge" in his book "The New Economics."

Numerous papers spearheaded the coalescing of the field. In 1935 Russian physiologist P.K. Anokhin published a book in which the concept of feedback ("back afferentation") was studied. The study and mathematical modelling of regulatory processes became a continuing research effort and two key articles were published in 1943. These papers were "Behavior, Purpose and Teleology" by Arturo Rosenblueth, Norbert Wiener, and Julian Bigelow; and the paper "A Logical Calculus of the Ideas Immanent in Nervous Activity" by Warren McCulloch and Walter Pitts.

Cybernetics as a discipline was firmly established by Wiener, McCulloch and others, such as W. Ross Ashby and W. Grey Walter.

Walter was one of the first to build autonomous robots as an aid to the study of animal behaviour. Together with the US and UK, an important geographical locus of early cybernetics was France.

In the spring of 1947, Wiener was invited to a congress on harmonic analysis, held in Nancy, France. The event was organized by the Bourbaki, a French scientific society, and mathematician Szolem Mandelbrojt (1899-1983), uncle of the world-famous mathematician Benoît Mandelbrot.

John von Neumann

During this stay in France, Wiener received the offer to write a manuscript on the unifying character of this part of applied mathematics, which is found in the study of Brownian motion and in telecommunication engineering. The following summer, back in the United States, Wiener decided to introduce the neologism cybernetics into his scientific theory. The name *cybernetics* was coined to denote the study of "teleological mechanisms" and was popularized through his book *Cybernetics, or Control and Communication in the Animal and Machine* (Hermann & Cie, Paris, 1948). In the UK this became the focus for the Ratio Club.

In the early 1940s John von Neumann, although better known for his work in mathematics and computer science, did contribute a unique and unusual addition to the world of cybernetics: Von Neumann cellular automata, and their logical follow up the Von Neumann Universal Constructor. The result of these deceptively simple thought-experiments was the concept of self replication which

cybernetics adopted as a core concept. The concept that the same properties of genetic reproduction applied to social memes, living cells, and even computer viruses is further proof of the somewhat surprising universality of cybernetic study.

Wiener popularized the social implications of cybernetics, drawing analogies between automatic systems (such as a regulated steam engine) and human institutions in his best-selling *The Human Use of Human Beings : Cybernetics and Society* (Houghton-Mifflin, 1950).

While not the only instance of a research organization focused on cybernetics, the Biological Computer Lab [5] at the University of Illinois, Urbana/Champaign, under the direction of Heinz von Foerster, was a major center of cybernetic research [6] for almost 20 years, beginning in 1958.

The fall and rebirth of cybernetics

For a time during the past 30 years, the field of cybernetics followed a boom-bust cycle of becoming more and more dominated by the subfields of artificial intelligence and machine-biological interfaces (ie. cyborgs) and when this research fell out of favor, the field as a whole fell from grace.

Francisco Varela.

In the 1970s new cyberneticians emerged in multiple fields, but especially in biology. The ideas of Maturana, Varela and Atlan, according to Dupuy (1986) "realized that the cybernetic metaphors of the program upon which molecular biology had been based rendered a conception of the autonomy of the living being impossible. Consequently, these thinkers were led to invent a new cybernetics, one more suited to the organizations which mankind discovers in nature - organizations he has not himself invented"[7] . However, during the 1980s the question of whether the features of this new cybernetics could be applied to social forms of organization remained open to debate.[7]

Stuart A. Umpleby

In political science, Project Cybersyn attempted to introduce a cybernetically controlled economy during the early 1970s. In the 1980s, according to Harries-Jones (1988) "unlike its predecessor, the new cybernetics concerns itself with the interaction of autonomous political actors and subgroups, and the practical and reflexive consciousness of the subjects who produce and reproduce the structure of a political community. A dominant consideration is that of recursiveness, or self-reference of political action both with regards to the expression of political consciousness and with the ways in which systems build upon themselves".[8]

One characteristic of the emerging new cybernetics considered in that time by Geyer and van der Zouwen, according to Bailey (1994), was "that it views information as constructed and reconstructed by an individual interacting with the environment. This provides an epistemological foundation of science, by viewing it as observer-dependent. Another characteristic of the new cybernetics is its contribution towards bridging the "micro-macro gap". That is, it links the individual with the society"[9] Another charateristic noted was the "transition from classical cybernetics to the new cybernetics [that] involves a transition from classical problems to new problems. These shifts in thinking involve, among others, (a) a change from emphasis on the system being steered to the system doing the steering, and the factor which guides the steering decisions.; and (b) new emphasis on communication between several systems which are trying to steer each

other"[9] . The work of Gregory Bateson was also strongly influenced by cybernetics.

Recent endeavors into the true focus of cybernetics, systems of control and emergent behavior, by such related fields as game theory (the analysis of group interaction), systems of feedback in evolution, and metamaterials (the study of materials with properties beyond the Newtonian properties of their constituent atoms), have led to a revived interest in this increasingly relevant field.[2]

Subdivisions of the field

Cybernetics is an earlier but still-used generic term for many types of subject matter. These subjects also extend into many others areas of science, but are united in their study of control of systems.

Pure cybernetics

Pure cybernetics studies systems of control as a concept, attempting to discover the basic principles underlying such things as

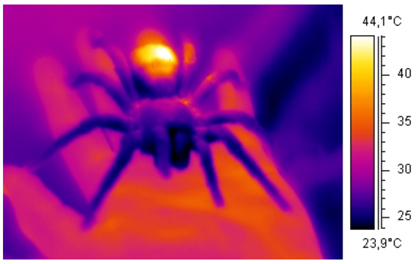
- Artificial intelligence
- Robotics
- Computer Vision
- Control systems
- Emergence
- Learning organization
- New Cybernetics
- Second-order cybernetics
- Interactions of Actors Theory
- Conversation Theory


ASIMO uses sensors and intelligent algorithms to avoid obstacles and navigate stairs.

In biology

Cybernetics in biology is the study of cybernetic systems present in biological organisms, primarily focusing on how animals adapt to their environment, and how information in the form of genes is passed from generation to generation[10] . There is also a secondary focus on combining artificial systems with biological systems.

- Bioengineering
- Biocybernetics
- Bionics
- Homeostasis
- Medical cybernetics
- Synthetic Biology
- Systems Biology



Thermal image of a cold-blooded tarantula on a warm-blooded human hand

In computer science

Computer science directly applies the concepts of cybernetics to the control of devices and the analysis of information.

- Robotics
- Decision support system
- Cellular automaton
- Simulation

In engineering

Cybernetics in engineering is used to analyze cascading failures and System Accidents, in which the small errors and imperfections in a system can generate disasters. Other topics studied include:

- Adaptive systems
- Engineering cybernetics
- Ergonomics
- Biomedical engineering
- Systems engineering

An artificial heart, a product of biomedical engineering.

In management

- Entrepreneurial cybernetics
- Management cybernetics
- Organizational cybernetics

- Operations research
- Systems engineering

In mathematics

Mathematical Cybernetics focuses on the factors of information, interaction of parts in systems, and the structure of systems.

- Dynamical system
- Information theory
- Systems theory

In psychology

- Homunculus
- Psycho-Cybernetics
- Systems psychology

In sociology

By examining group behavior through the lens of cybernetics, sociology seeks the reasons for such spontaneous events as smart mobs and riots, as well as how communities develop rules, such as etiquette, by consensus without formal discussion.Affect Control Theory explains role behavior, emotions, and labeling theory in terms of homeostatic maintenance of sentiments associated with cultural categories. The most comprehensive attempt ever made in the social sciences to increase cybernetics in a generalized theory of society was made by Talcott Parsons. These and other cybernetic models in sociology are reviewed in a book edited by McClelland and Fararo[11] .

- Affect Control Theory
- Memetics
- Sociocybernetics

Related fields

Complexity science

Complexity science attempts to understand the nature of complex systems.

- Complex Adaptive System
- Complex systems
- Complexity theory

See also

- Artificial life
- Automation
- Brain-computer interface
- Chaos theory
- Connectionism
- Decision theory
- Family therapy
- Gaia hypothesis
- Industrial Ecology
- Intelligence amplification
- Management science
- Perceptual control theory
- Principia Cybernetica
- Project Cybersyn
- Viable System Model
- Semiotics
- Superorganisms
- Synergetics

Further reading

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- Heinz von Foerster, (1995), Ethics and Second-Order Cybernetics [16].
- Stuart Umpleby (1989), "The science of cybernetics and the cybernetics of science" [17], in: *Cybernetics and Systems", Vol. 21, No. 1, (1990), pp. 109-121.*

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External links

General

- *Principia Cybernetica Web* [18]
- Web Dictionary of Cybernetics and Systems [19]
- Glossary Slideshow (136 slides) [20]
- Basics of Cybernetics [21]
- What is Cybernetics? [22] Livas short introductory videos on YouTube

Societies

- American Society for Cybernetics [23]
- IEEE Systems, Man, & Cybernetics Society [24]
- The Cybernetics Society [25]

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[5] http://www.ece.uiuc.edu/pubs/bcl/mueller/index.htm
[6] http://www.ece.uiuc.edu/pubs/bcl/hutchinson/index.htm
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[10] Note: this does not refer to the concept of Racial Memory but to the concept of cumulative adaptation to a particular niche, such as the case of the pepper moth having genes for both light and dark environments.
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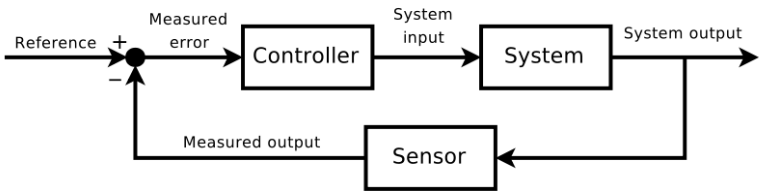
[12] http://pespmc1.vub.ac.be/books/IntroCyb.pdf
[13] http://pespmc1.vub.ac.be/Papers/Cybernetics-EPST.pdf
[14] http://pangaro.com/published/cyber-macmillan.html
[15] http://www.cybsoc.org/gcyb.htm
[16] http://www.stanford.edu/group/SHR/4-2/text/foerster.html
[17] ftp://ftp.vub.ac.be/pub/projects/Principia_Cybernetica/Papers_Umpleby/Science-Cybernetics.txt
[18] http://pespmc1.vub.ac.be/DEFAULT.html
[19] http://pespmc1.vub.ac.be/ASC/indexASC.html
[20] http://www.gwu.edu/~asc/slide/s1.html
[21] http://www.smithsrisca.demon.co.uk/cybernetics.html
[22] http://www.youtube.com/watch?v=_hjAXkNbPfk
[23] http://www.asc-cybernetics.org/
[24] http://www.ieeesmc.org/
[25] http://www.cybsoc.org

Control theory



The concept of the feedback loop to control the dynamic behavior of the system: this is negative feedback, because the sensed value is subtracted from the desired value to create the error signal which is amplified by the controller.

Control theory is an interdisciplinary branch of engineering and mathematics, that deals with the behavior of dynamical systems. The desired output of a system is called the *reference*. When one or more output variables of a system need to follow a certain reference over time, a controller manipulates the inputs to a system to obtain the desired effect on the output of the system.

Overview

Control theory is

- a theory that deals with influencing the behavior of dynamical systems
- an interdisciplinary subfield of science, which originated in engineering and mathematics, and evolved into use by the social sciences, like psychology, sociology and criminology.

An example

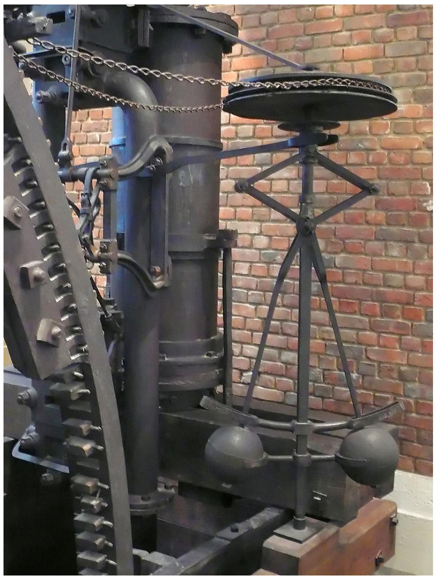
Consider an automobile's cruise control, which is a device designed to maintain a constant vehicle speed; the *desired* or *reference* speed, provided by the driver. The *system* in this case is the vehicle. The system output is the vehicle speed, and the control variable is the engine's throttle position which influences engine torque output.

A primitive way to implement cruise control is simply to lock the throttle position when the driver engages cruise control. However, on mountain terrain, the vehicle will slow down going uphill and accelerate going downhill. In fact, any parameter different than what was assumed at design time will translate into a proportional error in the output velocity, including exact mass of the vehicle, wind resistance, and tire pressure. This type of controller is called an open-loop controller because there is no direct connection between the output of the system (the vehicle's speed) and the actual conditions encountered; that is to say, the system does not and can not compensate for unexpected forces.

In a **closed-loop control system**, a sensor monitors the output (the vehicle's speed) and feeds the data to a computer which continuously adjusts the control input (the throttle) as necessary to keep the control error to a minimum (that is, to maintain the desired speed). Feedback on how the system is actually performing allows the controller (vehicle's on board computer) to dynamically compensate for disturbances to the system, such as changes in slope of the ground or wind speed. An ideal feedback control system cancels out all errors, effectively mitigating the effects of any forces that might or might not arise during operation and producing a response in the system that perfectly matches the user's wishes. In reality, this cannot be achieved due to measurement errors in the sensors, delays in the controller, and imperfections in the control input.

History

Although control systems of various types date back to antiquity, a more formal analysis of the field began with a dynamics analysis of the centrifugal governor, conducted by the physicist James Clerk Maxwell in 1868 entitled *On Governors*.[1] This described and analyzed the phenomenon of "hunting", in which lags in the system can lead to overcompensation and unstable behavior. This generated a flurry of interest in the topic, during which Maxwell's classmate Edward John Routh generalized the results of Maxwell for the general class of linear systems.[2] Independently, Adolf Hurwitz analyzed system stability using differential equations in 1877. This result is called the Routh-Hurwitz theorem.[3] [4]



Centrifugal governor in a Boulton & Watt engine of 1788

A notable application of dynamic control was in the area of manned flight. The Wright Brothers made their first successful test flights on December 17, 1903 and were distinguished by their ability to control their flights for substantial periods (more so than the ability to produce lift from an airfoil, which was known). Control of the airplane was necessary for safe flight.

By World War II, control theory was an important part of fire-control systems, guidance systems and electronics. The Space Race also depended on accurate spacecraft control. However, control theory also saw an increasing use in fields such as economics.

People in systems and control

Many active and historical figures made significant contribution to control theory, including, for example:

- Alexander Lyapunov (1857–1918) in the 1890s marks the beginning of stability theory.
- Harold S. Black (1898–1983), invented the concept of negative feedback amplifiers in 1927. He managed to develop stable negative feedback amplifiers in the 1930s.
- Harry Nyquist (1889–1976), developed the Nyquist stability criterion for feedback systems in the 1930s.
- Richard Bellman (1920–1984), developed dynamic programming since the 1940s.
- Andrey Kolmogorov (1903–1987) co-developed the Wiener-Kolmogorov filter (1941).
- Norbert Wiener (1894–1964) co-developed the Wiener-Kolmogorov filter and coined the term cybernetics in the 1940s.
- John R. Ragazzini (1912–1988) introduced digital control and the z-transform in the 1950s.
- Lev Pontryagin (1908–1988) introduced the maximum principle and the bang-bang principle.

Classical control theory

To avoid the problems of the open-loop controller, control theory introduces feedback. A closed-loop controller uses feedback to control states or outputs of a dynamical system. Its name comes from the information path in the system: process inputs (e.g. voltage applied to an electric motor) have an effect on the process outputs (e.g. velocity or torque of the motor), which is measured with sensors and processed by the controller; the result (the control signal) is used as input to the process, closing the loop.

Closed-loop controllers have the following advantages over open-loop controllers:

- disturbance rejection (such as unmeasured friction in a motor)

- guaranteed performance even with model uncertainties, when the model structure does not match perfectly the real process and the model parameters are not exact
- unstable processes can be stabilized
- reduced sensitivity to parameter variations
- improved reference tracking performance

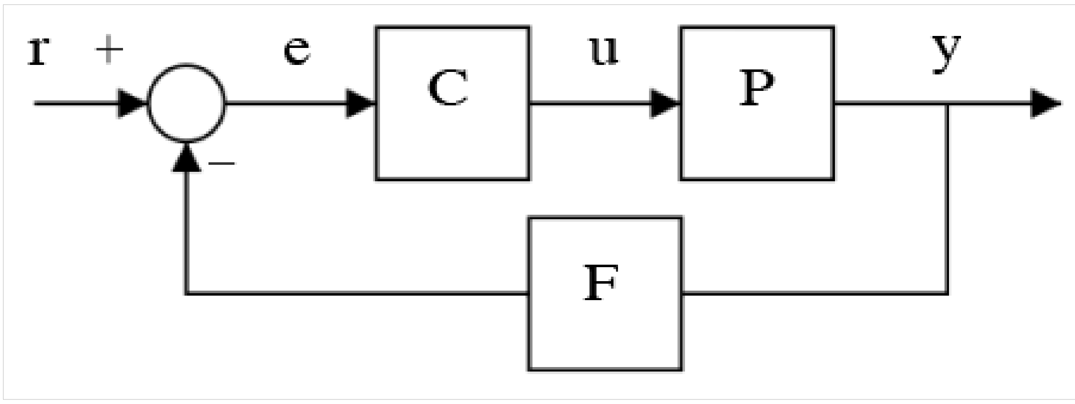
In some systems, closed-loop and open-loop control are used simultaneously. In such systems, the open-loop control is termed feedforward and serves to further improve reference tracking performance.

A common closed-loop controller architecture is the PID controller.

Closed-loop transfer function

The output of the system *y(t)* is fed back through a sensor measurement *F* to the reference value *r(t)*. The controller *C* then takes the error *e* (difference) between the reference and the output to change the inputs *u* to the system under control *P*. This is shown in the figure. This kind of controller is a closed-loop controller or feedback controller.

This is called a single-input-single-output (*SISO*) control system; *MIMO* (i.e. Multi-Input-Multi-Output) systems, with more than one input/output, are common. In such cases variables are represented through vectors instead of simple scalar values. For some distributed parameter systems the vectors may be infinite-dimensional (typically functions).



If we assume the controller *C*, the plant *P*, and the sensor *F* are linear and time-invariant (i.e.: elements of their transfer function *C(s)*, *P(s)*, and *F(s)* do not depend on time), the systems above can be analysed using the Laplace transform on the variables. This gives the following relations:

$$Y(s) = P(s)U(s)$$
$$U(s) = C(s)E(s)$$
$$E(s) = R(s) - F(s)Y(s).$$

Solving for *Y*(*s*) in terms of *R*(*s*) gives:

$$Y(s) = \left(\frac{P(s)C(s)}{1 + F(s)P(s)C(s)} \right) R(s) = H(s)R(s).$$

The expression $H(s) = \frac{P(s)C(s)}{1 + F(s)P(s)C(s)}$ is referred to as the *closed-loop transfer function* of the system.

The numerator is the forward (open-loop) gain from *r* to *y*, and the denominator is one plus the gain in going around the feedback loop, the so-called loop gain. If $|P(s)C(s)| \gg 1$, i.e. it has a large norm with each value of *s*, and if $|F(s)| \approx 1$, then *Y(s)* is approximately equal to *R(s)*. This simply means setting the reference to control the output.

PID controller

The PID controller is probably the most-used feedback control design. *PID* is an acronym for *Proportional-Integral-Derivative*, referring to the three terms operating on the error signal to produce a control signal. If *u(t)* is the control signal sent to the system, *y(t)* is the measured output and *r(t)* is the desired output, and tracking error $e(t) = r(t) - y(t)$, a PID controller has the general form

$$u(t) = K_P e(t) + K_I \int e(t) \mathrm{d}t + K_D \frac{\mathrm{d}}{\mathrm{d}t} e(t).$$

The desired closed loop dynamics is obtained by adjusting the three parameters K_P, K_I and K_D, often iteratively by "tuning" and without specific knowledge of a plant model. Stability can often be ensured using only the proportional term. The integral term permits the rejection of a step disturbance (often a striking specification in process control). The derivative term is used to provide damping or shaping of the response. PID controllers are the most well established class of control systems: however, they cannot be used in several more complicated cases, especially if MIMO systems are considered.

Applying Laplace transformation results in the transformed PID controller equation

$$u(s) = K_P e(s) + K_I \frac{1}{s} e(s) + K_D s e(s)$$

$$u(s) = (K_P + K_I \frac{1}{s} + K_D s) e(s)$$

with the PID controller transfer function

$$C(s) = (K_P + K_I \frac{1}{s} + K_D s).$$

Modern control theory

In contrast to the frequency domain analysis of the classical control theory, modern control theory utilizes the time-domain state space representation, a mathematical model of a physical system as a set of input, output and state variables related by first-order differential equations. To abstract from the number of inputs, outputs and states, the variables are expressed as vectors and the differential and algebraic equations are written in matrix form (the latter only being possible when the dynamical system is linear). The state space representation (also known as the "time-domain approach") provides a convenient and compact way to model and analyze systems with multiple inputs and outputs. With inputs and outputs, we would otherwise have to write down Laplace transforms to encode all the information about a system. Unlike the frequency domain approach, the use of the state space representation is not limited to systems with linear components and zero initial conditions. "State space" refers to the space whose axes are the state variables. The state of the system can be represented as a vector within that space.

Topics in control theory

Stability

The *stability* of a general dynamical system with no input can be described with Lyapunov stability criteria. A linear system that takes an input is called bounded-input bounded-output (BIBO) stable if its output will stay bounded for any bounded input. Stability for nonlinear systems that take an input is input-to-state stability (ISS), which combines Lyapunov stability and a notion similar to BIBO stability. For simplicity, the following descriptions focus on continuous-time and discrete-time linear systems.

Mathematically, this means that for a causal linear system to be stable all of the poles of its transfer function must satisfy some criteria depending on whether a continuous or discrete time analysis is used:

- In continuous time, the Laplace transform is used to obtain the transfer function. A system is stable if the poles of this transfer function lie strictly in the closed left half of the complex plane (i.e. the real part of all the poles is less than zero).
- In discrete time the Z-transform is used. A system is stable if the poles of this transfer function lie strictly inside the unit circle. i.e. the magnitude of the poles is less than one).

When the appropriate conditions above are satisfied a system is said to be asymptotically stable: the variables of an asymptotically stable control system always decrease from their initial value and do not show permanent oscillations. Permanent oscillations occur when a pole has a real part exactly equal to zero (in the continuous time case) or a modulus equal to one (in the discrete time case). If a simply stable system response neither decays nor grows over time, and has no oscillations, it is marginally stable: in this case the system transfer function has non-repeated poles at complex plane origin (i.e. their real and complex component is zero in the continuous time case). Oscillations are present when poles with real part equal to zero have an imaginary part not equal to zero.

Differences between the two cases are not a contradiction. The Laplace transform is in Cartesian coordinates and the Z-transform is in circular coordinates, and it can be shown that:

- the negative-real part in the Laplace domain can map onto the interior of the unit circle
- the positive-real part in the Laplace domain can map onto the exterior of the unit circle

If a system in question has an impulse response of

$$x[n] = 0.5^n u[n]$$

then the Z-transform (see this example), is given by

$$X(z) = \frac{1}{1 - 0.5z^{-1}}$$

which has a pole in $z = 0.5$(zero imaginary part). This system is BIBO (asymptotically) stable since the pole is *inside* the unit circle.

However, if the impulse response was

$$x[n] = 1.5^n u[n]$$

then the Z-transform is

$$X(z) = \frac{1}{1 - 1.5z^{-1}}$$

which has a pole at $z = 1.5$and is not BIBO stable since the pole has a modulus strictly greater than one.

Numerous tools exist for the analysis of the poles of a system. These include graphical systems like the root locus, Bode plots or the Nyquist plots.

Mechanical changes can make equipment (and control systems) more stable. Sailors add ballast to improve the stability of ships. Cruise ships use antiroll fins that extend transversely from the side of the ship for perhaps 30 feet (10 m) and are continuously rotated about their axes to develop forces that oppose the roll.

Controllability and observability

Controllability and observability are main issues in the analysis of a system before deciding the best control strategy to be applied, or whether it is even possible to control or stabilize the system. Controllability is related to the possibility of forcing the system into a particular state by using an appropriate control signal. If a state is not controllable, then no signal will ever be able to control the state. If a state is not controllable, but its dynamics are stable, then the state is termed Stabilizable. Observability instead is related to the possibility of "observing", through output measurements, the state of a system. If a state is not observable, the controller will never be able to determine the behaviour of an unobservable state and hence cannot use it to stabilize the system. However, similar to the stabilizability condition above, if a state cannot be observed it might still be detectable.

From a geometrical point of view, looking at the states of each variable of the system to be controlled, every "bad" state of these variables must be controllable and observable to ensure a good behaviour in the closed-loop system. That is, if one of the eigenvalues of the system is not both controllable and observable, this part of the dynamics will remain untouched in the closed-loop system. If such an eigenvalue is not stable, the dynamics of this eigenvalue will be present in the closed-loop system which therefore will be unstable. Unobservable poles are not present in the transfer function realization of a state-space representation, which is why sometimes the latter is preferred in dynamical systems analysis.

Solutions to problems of uncontrollable or unobservable system include adding actuators and sensors.

Control specifications

Several different control strategies have been devised in the past years. These vary from extremely general ones (PID controller), to others devoted to very particular classes of systems (especially robotics or aircraft cruise control).

A control problem can have several specifications. Stability, of course, is always present: the controller must ensure that the closed-loop system is stable, regardless of the open-loop stability. A poor choice of controller can even worsen the stability of the open-loop system, which must normally be avoided. Sometimes it would be desired to obtain particular dynamics in the closed loop: i.e. that the poles have $Re[\lambda] < -\overline{\lambda}$, where $\overline{\lambda}$ is a fixed value strictly greater than zero, instead of simply ask that $Re[\lambda] < 0$.
Another typical specification is the rejection of a step disturbance; including an integrator in the open-loop chain (i.e. directly before the system under control) easily achieves this. Other classes of disturbances need different types of sub-systems to be included.

Other "classical" control theory specifications regard the time-response of the closed-loop system: these include the rise time (the time needed by the control system to reach the desired value after a perturbation), peak overshoot (the highest value reached by the response before reaching the desired value) and others (settling time, quarter-decay). Frequency domain specifications are usually related to robustness (see after).

Modern performance assessments use some variation of integrated tracking error (IAE,ISA,CQI).

Model identification and robustness

A control system must always have some robustness property. A robust controller is such that its properties do not change much if applied to a system slightly different from the mathematical one used for its synthesis. This specification is important: no real physical system truly behaves like the series of differential equations used to represent it mathematically. Typically a simpler mathematical model is chosen in order to simplify calculations, otherwise the true system dynamics can be so complicated that a complete model is impossible.

System identification

The process of determining the equations that govern the model's dynamics is called system identification. This can be done off-line: for example, executing a series of measures from which to calculate an approximated mathematical model, typically its transfer function or matrix. Such identification from the output, however, cannot take account of unobservable dynamics. Sometimes the model is built directly starting from known physical equations: for example, in the case of a mass-spring-damper system we know that $m\ddot{x}(t) = -Kx(t) - \mathrm{B}\dot{x}(t)$. Even assuming that a "complete" model is used in designing the controller, all the parameters included in these equations (called "nominal parameters") are never known with absolute precision; the control system will have to behave correctly even when connected to physical system with true parameter values away from nominal.
Some advanced control techniques include an "on-line" identification process (see later). The parameters of the model are calculated ("identified") while the controller itself is running: in this way, if a drastic variation of the parameters ensues (for example, if the robot's arm releases a weight), the controller will adjust itself consequently in order to ensure the correct performance.

Analysis

Analysis of the robustness of a SISO control system can be performed in the frequency domain, considering the system's transfer function and using Nyquist and Bode diagrams. Topics include gain and phase margin and amplitude margin. For MIMO and, in general, more complicated control systems one must consider the theoretical results devised for each control technique (see next section): i.e., if particular robustness qualities are needed, the engineer must shift his attention to a control technique including them in its properties.

Constraints

A particular robustness issue is the requirement for a control system to perform properly in the presence of input and state constraints. In the physical world every signal is limited. It could happen that a controller will send control signals that cannot be followed by the physical system: for example, trying to rotate a valve at excessive speed. This can produce undesired behavior of the closed-loop system, or even break actuators or other subsystems. Specific control techniques are available to solve the problem: model predictive control (see later), and anti-wind up systems. The latter consists of an additional control block that ensures that the control signal never exceeds a given threshold.

System classifications

Linear control

For MIMO systems, pole placement can be performed mathematically using a state space representation of the open-loop system and calculating a feedback matrix assigning poles in the desired positions. In complicated systems this can require computer-assisted calculation capabilities, and cannot always ensure robustness. Furthermore, all system states are not in general measured and so observers must be included and incorporated in pole placement design.

Nonlinear control

Processes in industries like robotics and the aerospace industry typically have strong nonlinear dynamics. In control theory it is sometimes possible to linearize such classes of systems and apply linear techniques, but in many cases it can be necessary to devise from scratch theories permitting control of nonlinear systems. These, e.g., feedback linearization, backstepping, sliding mode control, trajectory linearization control normally take advantage of results based on Lyapunov's theory. Differential geometry has been widely used as a tool for generalizing well-known linear control concepts to the non-linear case, as well as showing the subtleties that make it a more challenging problem.

Main control strategies

Every control system must guarantee first the stability of the closed-loop behavior. For linear systems, this can be obtained by directly placing the poles. Non-linear control systems use specific theories (normally based on Aleksandr Lyapunov's Theory) to ensure stability without regard to the inner dynamics of the system. The possibility to fulfill different specifications varies from the model considered and the control strategy chosen. Here a summary list of the main control techniques is shown:

Adaptive control

> Adaptive control uses on-line identification of the process parameters, or modification of controller gains, thereby obtaining strong robustness properties. Adaptive controls were applied for the first time in the aerospace industry in the 1950s, and have found particular success in that field.

Hierarchical control

> A Hierarchical control system is a type of Control System in which a set of devices and governing software is arranged in a hierarchical tree. When the links in the tree are implemented by a computer network, then that hierarchical control system is also a form of Networked control system.

Intelligent control

Intelligent control uses various AI computing approaches like neural networks, Bayesian probability, fuzzy logic, machine learning, evolutionary computation and genetic algorithms to control a dynamic system.

Optimal control

Optimal control is a particular control technique in which the control signal optimizes a certain "cost index": for example, in the case of a satellite, the jet thrusts needed to bring it to desired trajectory that consume the least amount of fuel. Two optimal control design methods have been widely used in industrial applications, as it has been shown they can guarantee closed-loop stability. These are Model Predictive Control (MPC) and Linear-Quadratic-Gaussian control (LQG). The first can more explicitly take into account constraints on the signals in the system, which is an important feature in many industrial processes. However, the "optimal control" structure in MPC is only a means to achieve such a result, as it does not optimize a true performance index of the closed-loop control system. Together with PID controllers, MPC systems are the most widely used control technique in process control.

Robust control

Robust control deals explicitly with uncertainty in its approach to controller design. Controllers designed using *robust control* methods tend to be able to cope with small differences between the true system and the nominal model used for design. The early methods of Bode and others were fairly robust; the state-space methods invented in the 1960s and 1970s were sometimes found to lack robustness. A modern example of a robust control technique is H-infinity loop-shaping developed by Duncan McFarlane and Keith Glover of Cambridge University, United Kingdom. Robust methods aim to achieve robust performance and/or stability in the presence of small modeling errors.

Stochastic control

Stochastic control deals with control design with uncertainty in the model. In typical stochastic control problems, it is assumed that there exist random noise and disturbances in the model and the controller, and the control design must take into account these random deviations.

See also

Examples of control systems

- Automation
- Deadbeat Controller
- Distributed parameter systems
- Fractional order control
- H-infinity loop-shaping
- Hierarchical control system
- PID controller
- Model predictive control
- Process control
- Robust control
- Servomechanism
- State space (controls)

Topics in control theory

- Coefficient diagram method
- Control reconfiguration
- Feedback
- H infinity
- Hankel singular value
- Krener's theorem
- Lead-lag compensator
- Radial basis function
- Robotic unicycle
- Root locus
- Signal-flow graphs
- Stable polynomial
- Underactuation

Other related topics

- Automation and Remote Control
- Bond graph
- Control engineering
- Controller (control theory)
- Intelligent control
- Mathematical system theory
- Perceptual control theory
- Systems theory
- People in systems and control
- Time scale calculus
- Negative feedback amplifier

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External links

- Control Tutorials for Matlab [8] - A set of worked through control examples solved by several different methods.

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Genomics

Genomics is the study of the genomes of organisms. The field includes intensive efforts to determine the entire DNA sequence of organisms and fine-scale genetic mapping efforts. The field also includes studies of intragenomic phenomena such as heterosis, epistasis, pleiotropy and other interactions between loci and alleles within the genome. In contrast, the investigation of the roles and functions of single genes is a primary focus of molecular biology or genetics and is a common topic of modern medical and biological research. Research of single genes does not fall into the definition of genomics unless the aim of this genetic, pathway, and functional information analysis is to elucidate its effect on, place in, and response to the entire genome's networks.

For the United States Environmental Protection Agency, "the term "genomics" encompasses a broader scope of scientific inquiry associated technologies than when genomics was initially considered. A genome is the sum total of all an individual organism's genes. Thus, genomics is the study of all the genes of a cell, or tissue, at the DNA (genotype), mRNA (transcriptome), or protein (proteome) levels."[1]

History

Genomics was established by Fred Sanger when he first sequenced the complete genomes of a virus and a mitochondrion. His group established techniques of sequencing, genome mapping, data storage, and bioinformatic analyses in the 1970-1980s. A major branch of genomics is still concerned with sequencing the genomes of various organisms, but the knowledge of full genomes has created the possibility for the field of functional genomics, mainly concerned with patterns of gene expression during various conditions. The most important tools here are microarrays and bioinformatics. Study of the full set of proteins in a cell type or tissue, and the changes during various conditions, is called proteomics. A related concept is materiomics, which is defined as the study of the material properties of biological materials (e.g. hierarchical protein structures and materials, mineralized biological tissues, etc.) and their effect on the macroscopic function and failure in their biological context, linking processes, structure and properties at multiple scales through a materials science approach. The actual term 'genomics' is thought to have been coined by Dr. Tom Roderick, a geneticist at the Jackson Laboratory (Bar Harbor, ME) over beer at a meeting held in Maryland on the mapping of the human genome in 1986.

In 1972, Walter Fiers and his team at the Laboratory of Molecular Biology of the University of Ghent (Ghent, Belgium) were the first to determine the sequence of a gene: the gene for Bacteriophage MS2 coat protein.[2] In 1976, the team determined the complete nucleotide-sequence of bacteriophage MS2-RNA.[3] The first DNA-based genome to be sequenced in its entirety was that of bacteriophage Φ-X174; (5,368 bp), sequenced by Frederick Sanger in 1977.[4]

The first free-living organism to be sequenced was that of *Haemophilus influenzae* (1.8 Mb) in 1995, and since then genomes are being sequenced at a rapid pace.

As of September 2007, the complete sequence was known of about 1879 viruses [5] , 577 bacterial species and roughly 23 eukaryote organisms, of which about half are fungi. [6] Most of the bacteria whose genomes have been completely sequenced are problematic disease-causing agents, such as *Haemophilus influenzae*. Of the other sequenced species, most were chosen because they were well-studied model organisms or promised to become good models. Yeast (*Saccharomyces cerevisiae*) has long been an important model organism for the eukaryotic cell, while the fruit fly *Drosophila melanogaster* has been a very important tool (notably in early pre-molecular genetics). The worm *Caenorhabditis elegans* is an often used simple model for multicellular organisms. The zebrafish *Brachydanio rerio* is used for many developmental studies on the molecular level and the flower *Arabidopsis thaliana* is a model organism for flowering plants. The Japanese pufferfish (*Takifugu rubripes*) and the spotted green pufferfish (*Tetraodon nigroviridis*) are interesting because of their small and compact genomes, containing very little non-coding DNA compared to most species. [7] [8] The mammals dog (*Canis familiaris*), [9] brown rat (*Rattus

norvegicus), mouse (*Mus musculus*), and chimpanzee (*Pan troglodytes*) are all important model animals in medical research.

Human genomics

A rough draft of the human genome was completed by the Human Genome Project in early 2001, creating much fanfare. By 2007 the human sequence was declared "finished" (less than one error in 20,000 bases and all chromosomes assembled. Display of the results of the project required significant bioinformatics resources. The sequence of the human reference assembly can be explored using the UCSC Genome Browser.

Bacteriophage genomics

Bacteriophages have played and continue to play a key role in bacterial genetics and molecular biology. Historically, they were used to define gene structure and gene regulation. Also the first genome to be sequenced was a bacteriophage. However, bacteriophage research did not lead the genomics revolution, which is clearly dominated by bacterial genomics. Only very recently has the study of bacteriophage genomes become prominent, thereby enabling researchers to understand the mechanisms underlying phage evolution. Bacteriophage genome sequences can be obtained through direct sequencing of isolated bacteriophages, but can also be derived as part of microbial genomes. Analysis of bacterial genomes has shown that a substantial amount of microbial DNA consists of prophage sequences and prophage-like elements. A detailed database mining of these sequences offers insights into the role of prophages in shaping the bacterial genome.[10]

Cyanobacteria genomics

At present there are 24 cyanobacteria for which a total genome sequence is available. 15 of these cyanobacteria come from the marine environment. These are six *Prochlorococcus* strains, seven marine *Synechococcus* strains, *Trichodesmium erythraeum* IMS101 and *Crocosphaera watsonii* WH8501. Several studies have demonstrated how these sequences could be used very successfully to infer important ecological and physiological characteristics of marine cyanobacteria. However, there are many more genome projects currently in progress, amongst those there are further *Prochlorococcus* and marine *Synechococcus* isolates, *Acaryochloris* and *Prochloron*, the N_2-fixing filamentous cyanobacteria *Nodularia spumigena*, *Lyngbya aestuarii* and *Lyngbya majuscula*, as well as bacteriophages infecting marine cyanobaceria. Thus, the growing body of genome information can also be tapped in a more general way to address global problems by applying a comparative approach. Some new and exciting examples of progress in this field are the identification of genes for regulatory RNAs, insights into the evolutionary origin of photosynthesis, or estimation of the contribution of horizontal gene transfer to the genomes that have been analyzed.[11]

See also

- Full Genome Sequencing
- Computational genomics
- Nitrogenomics
- Metagenomics
- Predictive Medicine
- Personal genomics
- Psychogenomics

External links

- Genomics Directory [12]: A one-stop biotechnology resource center for bioentrepreneurs, scientists, and students
- Annual Review of Genomics and Human Genetics [13]
- BMC Genomics [14]: A BMC journal on Genomics
- Genomics [15]: UK companies and laboratories* Genomics journal [16]
- Genomics.org [17]: An openfree wiki based Genomics portal
- NHGRI [18]: US government's genome institute
- Pharmacogenomics in Drug Discovery and Development [19], a book on pharmacogenomics, diseases, personalized medicine, and therapeutics
- Tishchenko P. D. Genomics: New Science in the New Cultural Situation [20]
- Undergraduate program on Genomic Sciences (spanish) [21]: One of the first undergraduate programs in the world
- JCVI Comprehensive Microbial Resource [22]
- Pathema: A Clade Specific Bioinformatics Resource Center [23]
- KoreaGenome.org [24]: The first Korean Genome published and the sequence is available freely.
- GenomicsNetwork [25]: Looks at the development and use of the science and technologies of genomics.
- Institute for Genome Science [26]: Genomics research.

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Interactomics

Interactomics is a discipline at the intersection of bioinformatics and biology that deals with studying both the interactions and the consequences of those interactions between and among proteins, and other molecules within a cell[1] . The network of all such interactions is called the Interactome. Interactomics thus aims to compare such networks of interactions (i.e., interactomes) between and within species in order to find how the traits of such networks are either preserved or varied. From a mathematical, or mathematical biology viewpoint an interactome network is a graph or a category representing the most important interactions pertinent to the normal physiological functions of a cell or organism.

Interactomics is an example of "top-down" systems biology, which takes an overhead, as well as overall, view of a biosystem or organism. Large sets of genome-wide and proteomic data are collected, and correlations between different molecules are inferred. From the data new hypotheses are formulated about feedbacks between these molecules. These hypotheses can then be tested by new experiments[2] .

Through the study of the interaction of all of the molecules in a cell the field looks to gain a deeper understanding of genome function and evolution than just examining an individual genome in isolation[1] . Interactomics goes beyond cellular proteomics in that it not only attempts to characterize the interaction between proteins, but between all molecules in the cell.

Methods of interactomics

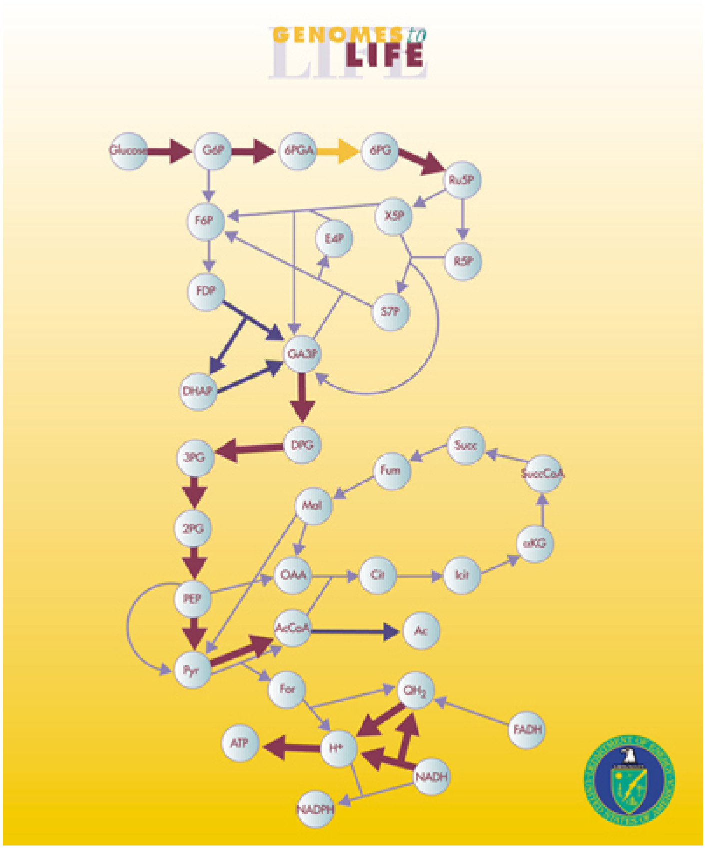
The study of the interactome requires the collection of large amounts of data by way of high throughput experiments. Through these experiments a large number of data points are collected from a single organism under a small number of perturbations[2] These experiments include:

- Two-hybrid screening
- Tandem Affinity Purification
- X-ray tomography
- Optical fluorescence microscopy

Recent developments

The field of interactomics is currently rapidly expanding and developing. While no biological interactomes have been fully characterized. Over 90% of proteins in *Saccharomyces cerevisiae* have been screened and their interactions characterized, making it the first interactome to be nearly fully specified [3] .

Also there have been recent systematic attempts to explore the human interactome[1] and [4] .



Metabolic Network Model for Escherichia coli.

Other species whose interactomes have been studied in some detail include *Caenorhabditis elegans* and *Drosophila melanogaster*.

Criticisms and concerns

Kiemer and Cesareni[1] raise the following concerns with the current state of the field:

- The experimental procedures associated with the field are error prone leading to "noisy results". This leads to 30% of all reported interactions being artifacts. In fact, two groups using the same techniques on the same organism found less than 30% interactions in common.
- Techniques may be biased, i.e. the technique determines which interactions are found.
- Ineractomes are not nearly complete with perhaps the exception of *S. cerivisiae*.
- While genomes are stable, interactomes may vary between tissues and developmental stages.
- Genomics compares amino acids, and nucleotides which are in a sense unchangeable, but interactomics compares proteins and other molecules which are subject to mutation and evolution.
- It is difficult to match evolutionarily related proteins in distantly related species.

See also

- Interaction network
- Proteomics
- Metabolic network
- Metabolic network modelling
- Metabolic pathway
- Genomics
- Mathematical biology
- Systems biology

External links

- Interactomics.org [5]. A dedicated interactomics web site operated under BioLicense.
- Interactome.org [6]. An interactome wiki site.
- PSIbase [7] Structural Interactome Map of all Proteins.
- Omics.org [8]. An omics portal site that is openfree (under BioLicense)
- Genomics.org [17]. A Genomics wiki site.
- Comparative Interactomics analysis of protein family interaction networks using PSIMAP (protein structural interactome map) [9]
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- Using convex hulls to extract interaction interfaces from known structures. Panos Dafas, Dan Bolser, Jacek Gomoluch, Jong Park, and Michael Schroeder. Bioinformatics 2004 20: 1486-1490.
- PSIbase: a database of Protein Structural Interactome map (PSIMAP). Sungsam Gong, Giseok Yoon, Insoo Jang Bioinformatics 2005.
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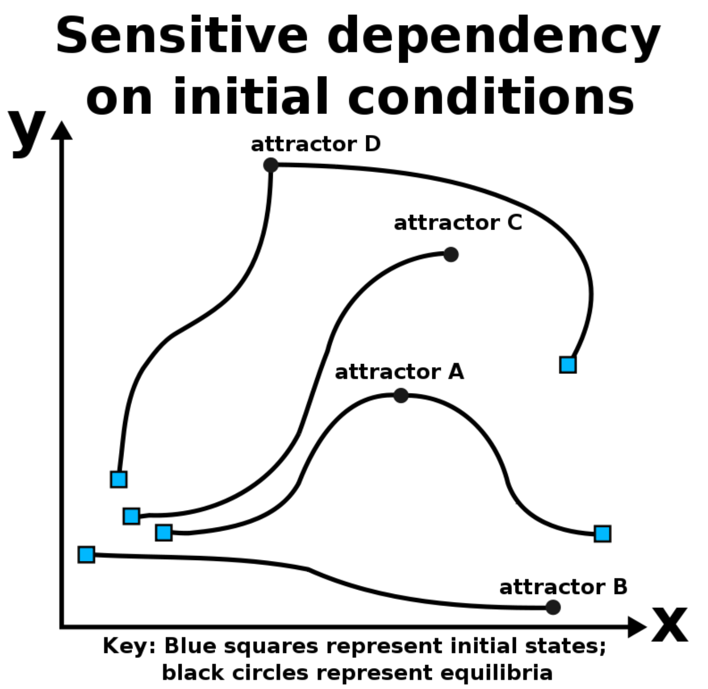
Chaotic Dynamics

Butterfly effect

The **butterfly effect** is a metaphor that encapsulates the concept of *sensitive dependence on initial conditions* in chaos theory; namely that small differences in the initial condition of a dynamical system may produce large variations in the long term behavior of the system. Although this may appear to be an esoteric and unusual behavior, it is exhibited by very simple systems: for example, a ball placed at the crest of a hill might roll into any of several valleys depending on slight differences in initial position. The butterfly effect is a common trope in fiction when presenting scenarios involving time travel and with "what if" scenarios where one storyline diverges at the moment of a seemingly minor event resulting in two significantly different outcomes.



Point attractors in 2D phase space.

Theory

Recurrence, the approximate return of a system towards its initial conditions, together with sensitive dependence on initial conditions are the two main ingredients for chaotic motion. They have the practical consequence of making complex systems, such as the weather, difficult to predict past a certain time range (approximately a week in the case of weather), since it is impossible to measure the starting atmospheric conditions completely accurately.

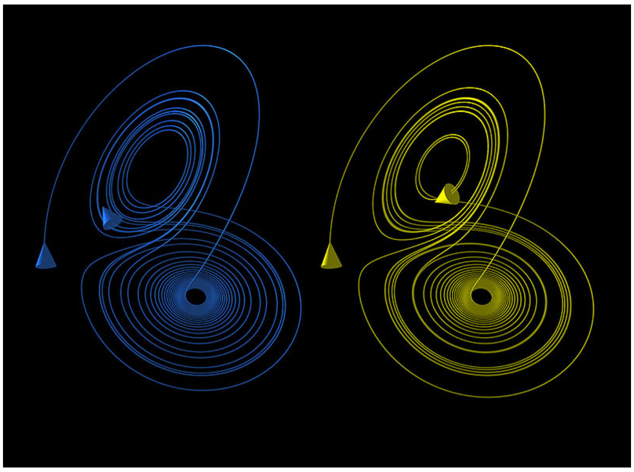
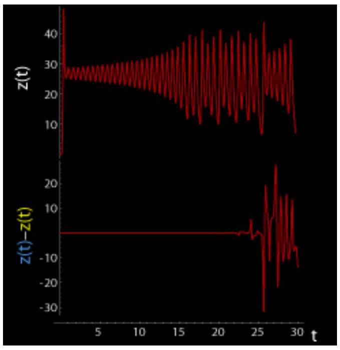
Origin of the concept and the term

The term "butterfly effect" itself is related to the work of Edward Lorenz, and is based in chaos theory and sensitive dependence on initial conditions, already described in the literature in a particular case of the three-body problem by Henri Poincaré in 1890[1] . He even later proposed that such phenomena could be common, say in meteorology. In 1898[2] Jacques Hadamard noted general divergence of trajectories in spaces of negative curvature, and Pierre Duhem discussed the possible general significance of this in 1908[3] . The idea that one butterfly could eventually have a far-reaching ripple effect on subsequent historic events seems first to have appeared in a 1952 short story by Ray Bradbury about time travel (see Literature and print here) although Lorenz made the term popular. In 1961, Lorenz was using a numerical computer model to rerun a weather prediction, when, as a shortcut on a number in the sequence, he entered the decimal .506 instead of entering the full .506127 the computer would hold. The result was a completely different weather scenario.[4] Lorenz published his findings in a 1963 paper for the New York Academy of Sciences noting that "One meteorologist remarked that if the theory were correct, one flap of a seagull's wings

could change the course of weather forever." Later speeches and papers by Lorenz used the more poetic butterfly. According to Lorenz, upon failing to provide a title for a talk he was to present at the 139th meeting of the American Association for the Advancement of Science in 1972, Philip Merilees concocted *Does the flap of a butterfly’s wings in Brazil set off a tornado in Texas?* as a title. Although a butterfly flapping its wings has remained constant in the expression of this concept, the location of the butterfly, the consequences, and the location of the consequences have varied widely.[5]

The phrase refers to the idea that a butterfly's wings might create tiny changes in the atmosphere that may ultimately alter the path of a tornado or delay, accelerate or even prevent the occurrence of a tornado in a certain location. The flapping wing represents a small change in the initial condition of the system, which causes a chain of events leading to large-scale alterations of events (compare: domino effect). Had the butterfly not flapped its wings, the trajectory of the system might have been vastly different. While the butterfly does not "cause" the tornado in the sense of providing the energy for the tornado, it does "cause" it in the sense that the flap of its wings is an essential part of the initial conditions resulting in a tornado, and without that flap that particular tornado would not have existed.

Illustration

<table>
<tr><th colspan="2">The butterfly effect in the Lorenz attractor</th></tr>
<tr><td>time 0 ≤ t ≤ 30 (larger)</td><td>z coordinate (larger)</td></tr>
<tr><td></td><td>
</td></tr>
<tr><td colspan="2">These figures show two segments of the three-dimensional evolution of two trajectories (one in blue, the other in yellow) for the same period of time in the Lorenz attractor starting at two initial points that differ only by 10^{-5} in the x-coordinate. Initially, the two trajectories seem coincident, as indicated by the small difference between the z coordinate of the blue and yellow trajectories, but for $t > 23$ the difference is as large as the value of the trajectory. The final position of the cones indicates that the two trajectories are no longer coincident at t=30.</td></tr>
<tr><td colspan="2">A Java animation of the Lorenz attractor [6] shows the continuous evolution.</td></tr>
</table>

Mathematical definition

A dynamical system with evolution map f^t displays sensitive dependence on initial conditions if points arbitrarily close become separate with increasing *t*. If *M* is the state space for the map f^t, then f^t displays sensitive dependence to initial conditions if there is a δ>0 such that for every point *x*∈M and any neighborhood *N* containing *x* there exist a point *y* from that neighborhood *N* and a time τ such that the distance

$$d(f^\tau(x), f^\tau(y)) > \delta \,.$$

The definition does not require that all points from a neighborhood separate from the base point *x*.

Examples in semiclassical and quantum physics

The potential for sensitive dependence on initial conditions (the butterfly effect) has been studied in a number of cases in semiclassical and quantum physics including atoms in strong fields and the anisotropic Kepler problem.[7] [8] Some authors have argued that extreme (exponential) dependence on initial conditions is not expected in pure quantum treatments;[9] [10] however, the sensitive dependence on initial conditions demonstrated in classical motion is included in the semiclassical treatments developed by Martin Gutzwiller[11] and Delos and co-workers.[12]

Other authors suggest that the butterfly effect can be observed in quantum systems. Karkuszewski et al. consider the time evolution of quantum systems which have slightly different Hamiltonians. They investigate the level of sensitivity of quantum systems to small changes in their given Hamiltonians.[13] Poulin et al. present a quantum algorithm to measure fidelity decay, which “measures the rate at which identical initial states diverge when subjected to slightly different dynamics.” They consider fidelity decay to be “the closest quantum analog to the (purely classical) butterfly effect.”[14] Whereas the classical butterfly effect considers the effect of a small change in the position and/or velocity of an object in a given Hamiltonian system, the quantum butterfly effect considers the effect of a small change in the Hamiltonian system with a given initial position and velocity.[15] [16] This quantum butterfly effect has been demonstrated experimentally.[17] Quantum and semiclassical treatments of system sensitivity to initial conditions are known as quantum chaos.[9] [18]

See also

- Avalanche effect
- Behavioral Cusp
- Black swan theory
- Cascading failure
- Causality
- Chain reaction
- Determinism
- Domino effect
- Dynamical systems
- Fractal
- Snowball effect

Further reading

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- Robert C. Hilborn (2004). "Sea gulls, butterflies, and grasshoppers: A brief history of the butterfly effect in nonlinear dynamics". *American Journal of Physics* **72**: 425–427. doi:10.1119/1.1636492.

External links

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- From butterfly wings to single e-mail [20] (Cornell University)
- New England Complex Systems Institute - Concepts: Butterfly Effect [21]
- The Chaos Hypertextbook [22]. An introductory primer on chaos and fractals.
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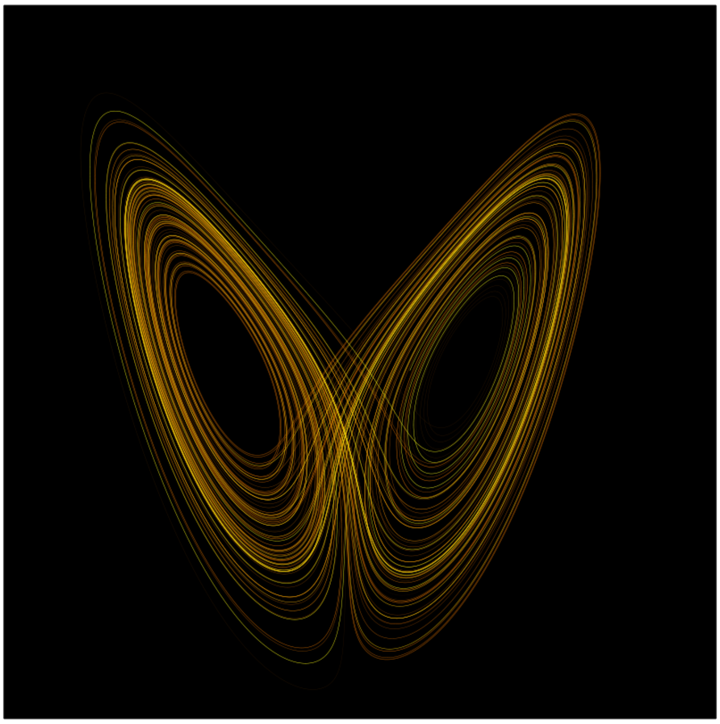
Chaos theory



A plot of the Lorenz attractor for values $r = 28$, $\sigma = 10$, $b = 8/3$

Chaos theory is a field of study in mathematics, physics, and philosophy studying the behavior of dynamical systems that are highly sensitive to initial conditions. This sensitivity is popularly referred to as the butterfly effect. Small differences in initial conditions (such as those due to rounding errors in numerical computation) yield widely diverging outcomes for chaotic systems, rendering long-term prediction impossible in general.[1] This happens even though these systems are deterministic, meaning that their future behaviour is fully determined by their initial conditions, with no random elements involved.[2] In other words, the deterministic nature of these systems does not make them predictable.[3] This behavior is known as deterministic chaos, or simply *chaos*.

Chaotic behavior can be observed in many natural systems, such as the weather.[4] Explanation of such behavior may be sought through analysis of a chaotic mathematical model, or through analytical techniques such as recurrence plots and Poincaré maps.

Applications

Chaos theory is applied in many scientific disciplines: mathematics, programming, microbiology, biology, computer science, economics,[5] [6] [7] engineering,[8] finance,[9] [10] philosophy, physics, politics, population dynamics, psychology, and robotics.[11]

Chaotic behavior has been observed in the laboratory in a variety of systems including electrical circuits, lasers, oscillating chemical reactions, fluid dynamics, and mechanical and magneto-mechanical devices, as well as computer models of chaotic processes. Observations of chaotic behavior in nature include changes in weather,[4] the dynamics of satellites in the solar system, the time evolution of the magnetic field of celestial bodies, population growth in ecology, the dynamics of the action potentials in neurons, and molecular vibrations. There is some controversy over the existence of chaotic dynamics in plate tectonics and in economics.[12] [13] [14]

One of the most successful applications of chaos theory has been in ecology, where dynamical systems such as the Ricker model have been used to show how population growth under density dependence can lead to chaotic dynamics.

Chaos theory is also currently being applied to medical studies of epilepsy, specifically to the prediction of seemingly random seizures by observing initial conditions.[15]

A related field of physics called quantum chaos theory investigates the relationship between chaos and quantum mechanics. The correspondence principle states that classical mechanics is a special case of quantum mechanics, the classical limit. If quantum mechanics does not demonstrate an exponential sensitivity to initial conditions, it is unclear how exponential sensitivity to initial conditions can arise in practice in classical chaos.[16] Recently, another

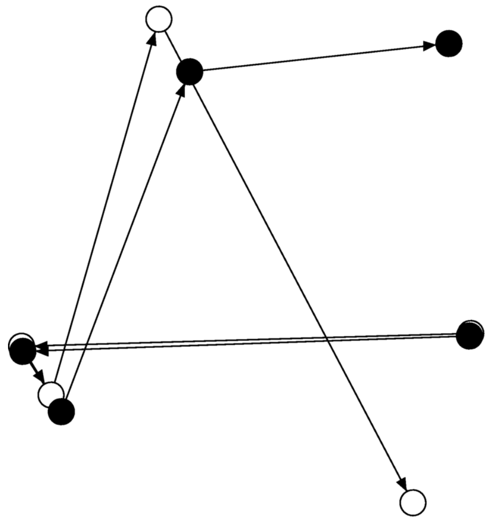
field, called relativistic chaos,[17] has emerged to describe systems that follow the laws of general relativity.

The initial conditions of three or more bodies interacting through gravitational attraction (see the *n*-body problem) can be arranged to produce chaotic motion.

Chaotic dynamics

In common usage, "chaos" means "a state of disorder",[18] but the adjective "chaotic" is defined more precisely in chaos theory. Although there is no universally accepted mathematical definition of chaos, a commonly-used definition says that, for a dynamical system to be classified as chaotic, it must have the following properties:[19]

1. it must be sensitive to initial conditions,
2. it must be topologically mixing, and
3. its periodic orbits must be dense.



The map defined by $x \to 4\,x\,(1-x)$ and $y \to x + y$ if $x + y < 1$ ($x + y - 1$ otherwise) displays sensitivity to initial conditions. Here two series of x and y values diverge markedly over time from a tiny initial difference.

Sensitivity to initial conditions

Sensitivity to initial conditions means that each point in such a system is arbitrarily closely approximated by other points with significantly different future trajectories. Thus, an arbitrarily small perturbation of the current trajectory may lead to significantly different future behaviour. However, it has been shown that the last two properties in the list above actually imply sensitivity to initial conditions[20] [21] and if attention is restricted to intervals, the second property implies the other two[22] (an alternative, and in general weaker, definition of chaos uses only the first two properties in the above list[23]). It is interesting that the most practically significant condition, that of sensitivity to initial conditions, is actually redundant in the definition, being implied by two (or for intervals, one) purely topological conditions, which are therefore of greater interest to mathematicians.

Sensitivity to initial conditions is popularly known as the "butterfly effect," so called because of the title of a paper given by Edward Lorenz in 1972 to the American Association for the Advancement of Science in Washington, D.C. entitled *Predictability: Does the Flap of a Butterfly's Wings in Brazil set off a Tornado in Texas?* The flapping wing represents a small change in the initial condition of the system, which causes a chain of events leading to large-scale phenomena. Had the butterfly not flapped its wings, the trajectory of the system might have been vastly different (even the evolution of simple discrete systems, such as cellular automata, can heavily depend on initial conditions, and Stephen Wolfram has investigated a cellular automaton with this property, termed by him *rule 30*).

A consequence of sensitivity to initial conditions is that if we start with only a finite amount of information about the system (as is usually the case in practice), then beyond a certain time the system will no longer be predictable. This is most familiar in the case of weather, which is generally predictable only about a week ahead.[24]

The Lyapunov exponent characterises the extent of the sensitivity to initial conditions. Quantitatively, two trajectories in phase space with initial separation $\delta\mathbf{Z}_0$ diverge

$$|\delta\mathbf{Z}(t)| \approx e^{\lambda t}|\delta\mathbf{Z}_0|$$

where λ is the Lyapunov exponent. The rate of separation can be different for different orientations of the initial separation vector. Thus, there is a whole spectrum of Lyapunov exponents — the number of them is equal to the number of dimensions of the phase space. It is common to just refer to the largest one, i.e. to the Maximal Lyapunov exponent (MLE), because it determines the overall predictability of the system. A positive MLE is usually taken as

an indication that the system is chaotic.

Topological mixing

Topological mixing (or topological *transitivity*) means that the system will evolve over time so that any given region or open set of its phase space will eventually overlap with any other given region. This mathematical concept of "mixing" corresponds to the standard intuition, and the mixing of colored dyes or fluids is an example of a chaotic system.

The map defined by $x \to 4\,x\,(1 - x)$ and $y \to x + y$ if $x + y < 1$ ($x + y - 1$ otherwise) also displays topological mixing. Here the blue region is transformed by the dynamics first to the purple region, then to the pink and red regions, and eventually to a cloud of points scattered across the space.

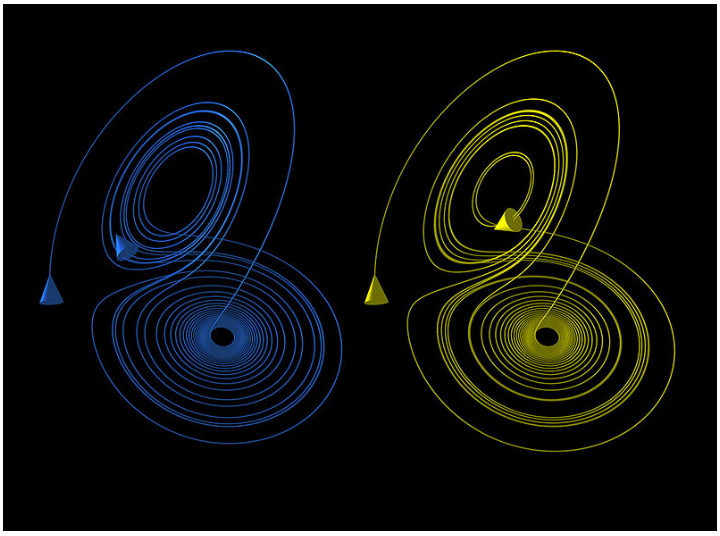
Topological mixing is often omitted from popular accounts of chaos, which equate chaos with sensitivity to initial conditions. However, sensitive dependence on initial conditions alone does not give chaos. For example, consider the simple dynamical system produced by repeatedly doubling an initial value. This system has sensitive dependence on initial conditions everywhere, since any pair of nearby points will eventually become widely separated. However, this example has no topological mixing, and therefore has no chaos. Indeed, it has extremely simple behaviour: all points except 0 tend to infinity.

Density of periodic orbits

Density of periodic orbits means that every point in the space is approached arbitrarily closely by periodic orbits. Topologically mixing systems failing this condition may not display sensitivity to initial conditions, and hence may not be chaotic. For example, an irrational rotation of the circle is topologically transitive, but does not have dense periodic orbits, and hence does not have sensitive dependence on initial conditions.[25] The one-dimensional logistic map defined by $x \to 4\,x\,(1 - x)$ is one of the simplest systems with density of periodic orbits. For example, $0.3454915 \to 0.9045085 \to 0.3454915$ is an (unstable) orbit of period 2, and similar orbits exist for periods 4, 8, 16, etc. (indeed, for all the periods specified by Sharkovskii's theorem).[26]

Sharkovskii's theorem is the basis of the Li and Yorke[27] (1975) proof that any one-dimensional system which exhibits a regular cycle of period three will also display regular cycles of every other length as well as completely chaotic orbits.

Strange Attractors



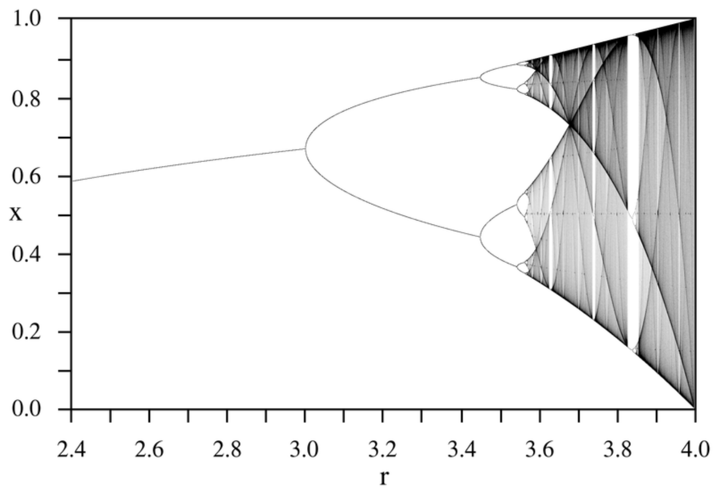
The Lorenz attractor displays chaotic behavior. These two plots demonstrate sensitive dependence on initial conditions within the region of phase space occupied by the attractor.

Some dynamical systems, like the one-dimensional logistic map defined by $x \to 4\,x\,(1 - x)$, are chaotic everywhere, but in many cases chaotic behaviour is found only in a subset of phase space. The cases of most interest arise when the chaotic behaviour takes place on an attractor, since then a large set of initial conditions will lead to orbits that converge to this chaotic region.

An easy way to visualize a chaotic attractor is to start with a point in the basin of attraction of the attractor, and then simply plot its subsequent orbit. Because of the topological transitivity condition, this is likely to produce a picture of the entire final attractor, and indeed both orbits shown in the figure on the right give a picture of the general shape of the Lorenz attractor. This attractor results from a simple three-dimensional model of the Lorenz weather system. The Lorenz attractor is perhaps one of the best-known chaotic system diagrams, probably because it was not only one of the first, but it is also one of the most complex and as such gives rise to a very interesting pattern which looks like the wings of a butterfly.

Unlike fixed-point attractors and *limit cycles*, the attractors which arise from chaotic systems, known as *strange attractors*, have great detail and complexity. Strange attractors occur in both continuous dynamical systems (such as the Lorenz system) and in some discrete systems (such as the Hénon map). Other discrete dynamical systems have a repelling structure called a Julia set which forms at the boundary between basins of attraction of fixed points – Julia sets can be thought of as strange *repellers*. Both strange attractors and Julia sets typically have a fractal structure, and a fractal dimension can be calculated for them.

Minimum complexity of a chaotic system



Bifurcation diagram of the logistic map $x \to r\,x\,(1-x)$. Each vertical slice shows the attractor for a specific value of r. The diagram displays period-doubling as r increases, eventually producing chaos.

Discrete chaotic systems, such as the logistic map, can exhibit strange attractors whatever their dimensionality. However, the Poincaré-Bendixson theorem shows that a strange attractor can only arise in a continuous dynamical system (specified by differential equations) if it has three or more dimensions. Finite dimensional linear systems are never chaotic; for a dynamical system to display chaotic behaviour it has to be either nonlinear, or infinite-dimensional.

The Poincaré–Bendixson theorem states that a two dimensional differential equation has very regular behavior. The Lorenz attractor discussed above is generated by a system of three differential equations with a total of seven terms on the right hand side, five of which are linear terms and two of which are quadratic (and therefore nonlinear). Another well-known chaotic attractor is generated by the Rossler equations with seven terms on the right hand side, only one of which is (quadratic) nonlinear. Sprott[28] found a three dimensional system with just five terms on the right hand side, and with just one quadratic nonlinearity, which exhibits chaos for certain parameter values. Zhang and Heidel[29] [30] showed that, at least for dissipative and conservative quadratic systems, three dimensional quadratic systems with only three or four terms on the right hand side cannot exhibit chaotic behavior. The reason is, simply put, that solutions to such systems are asymptotic to a two dimensional surface and therefore solutions are well behaved.

While the Poincaré–Bendixson theorem means that a continuous dynamical system on the Euclidean plane cannot be chaotic, two-dimensional continuous systems with non-Euclidean geometry can exhibit chaotic behaviour. Perhaps surprisingly, chaos may occur also in linear systems, provided they are infinite-dimensional.[31] A theory of linear chaos is being developed in the functional analysis, a branch of mathematical analysis.

History

The first discoverer of chaos was Henri Poincaré. In the 1880s, while studying the three-body problem, he found that there can be orbits which are nonperiodic, and yet not forever increasing nor approaching a fixed point.[32][33] In 1898 Jacques Hadamard published an influential study of the chaotic motion of a free particle gliding frictionlessly on a surface of constant negative curvature.[34] In the system studied, "Hadamard's billiards," Hadamard was able to show that all trajectories are unstable in that all particle trajectories diverge exponentially from one another, with a positive Lyapunov exponent.

Barnsley fern created using the chaos game. Natural forms (ferns, clouds, mountains, etc.) may be recreated through an Iterated function system (IFS).

Much of the earlier theory was developed almost entirely by mathematicians, under the name of ergodic theory. Later studies, also on the topic of nonlinear differential equations, were carried out by G.D. Birkhoff,[35] A. N. Kolmogorov,[36] [37] [38] M.L. Cartwright and J.E. Littlewood,[39] and Stephen Smale.[40] Except for Smale, these studies were all directly inspired by physics: the three-body problem in the case of Birkhoff, turbulence and astronomical problems in the case of Kolmogorov, and radio engineering in the case of Cartwright and Littlewood. Although chaotic planetary motion had not been observed, experimentalists had encountered turbulence in fluid motion and nonperiodic oscillation in radio circuits without the benefit of a theory to explain what they were seeing.

Despite initial insights in the first half of the twentieth century, chaos theory became formalized as such only after mid-century, when it first became evident for some scientists that linear theory, the prevailing system theory at that time, simply could not explain the observed behaviour of certain experiments like that of the logistic map. What had been beforehand excluded as measure imprecision and simple "noise" was considered by chaos theories as a full component of the studied systems.

The main catalyst for the development of chaos theory was the electronic computer. Much of the mathematics of chaos theory involves the repeated iteration of simple mathematical formulas, which would be impractical to do by hand. Electronic computers made these repeated calculations practical, while figures and images made it possible to visualize these systems.

Turbulence in the tip vortex from an airplane wing. Studies of the critical point beyond which a system creates turbulence was important for Chaos theory, analyzed for example by the Soviet physicist Lev Landau who developed the Landau-Hopf theory of turbulence. David Ruelle and Floris Takens later predicted, against Landau, that fluid turbulence could develop through a strange attractor, a main concept of chaos theory.

An early pioneer of the theory was Edward Lorenz whose interest in chaos came about accidentally through his work on weather prediction in 1961.[41] Lorenz was using a simple digital computer, a Royal McBee LGP-30, to run his weather simulation. He wanted to see a sequence of data again and to save time he started the simulation in the middle of its course. He was able to do this by entering a printout of the data corresponding to conditions in the middle of his simulation which he had calculated last time.

To his surprise the weather that the machine began to predict was completely different from the weather calculated before. Lorenz tracked this down to the computer printout. The computer worked with 6-digit precision, but the printout rounded variables off to a 3-digit number, so a value like 0.506127 was printed as 0.506. This difference is tiny and the consensus at the time would have been that it should have had practically no effect. However Lorenz had discovered that small changes in initial conditions produced large changes in the long-term outcome.[42] Lorenz's discovery, which gave its name to Lorenz attractors, proved that meteorology could not reasonably predict weather beyond a weekly period (at most).

The year before, Benoît Mandelbrot found recurring patterns at every scale in data on cotton prices.[43] Beforehand, he had studied information theory and concluded noise was patterned like a Cantor set: on any scale the proportion of noise-containing periods to error-free periods was a constant – thus errors were inevitable and must be planned for by incorporating redundancy.[44] Mandelbrot described both the "Noah effect" (in which sudden discontinuous changes can occur, e.g., in a stock's prices after bad news, thus challenging normal distribution theory in statistics, aka Bell Curve) and the "Joseph effect" (in which persistence of a value can occur for a while, yet suddenly change afterwards).[45] [46] In 1967, he published "How long is the coast of Britain? Statistical self-similarity and fractional dimension," showing that a coastline's length varies with the scale of the measuring instrument, resembles itself at all scales, and is infinite in length for an infinitesimally small measuring device.[47] Arguing that a ball of twine appears to be a point when viewed from far away (0-dimensional), a ball when viewed from fairly near (3-dimensional), or a curved strand (1-dimensional), he argued that the dimensions of an object are relative to the observer and may be fractional. An object whose irregularity is constant over different scales ("self-similarity") is a fractal (for example, the Koch curve or "snowflake", which is infinitely long yet encloses a finite space and has fractal dimension equal to circa 1.2619, the Menger sponge and the Sierpiński gasket). In 1975 Mandelbrot published *The Fractal Geometry of Nature*, which became a classic of chaos theory. Biological systems such as the branching of the circulatory and bronchial systems proved to fit a fractal model.

Chaos was observed by a number of experimenters before it was recognized; e.g., in 1927 by van der Pol[48] and in 1958 by R.L. Ives.[49] [50] However, as a graduate student in Chihiro Hayashi's laboratory at Kyoto University, Yoshisuke Ueda was experimenting with analog computers (that is, vacuum tubes) and noticed, on Nov. 27, 1961, what he called "randomly transitional phenomena". Yet his advisor did not agree with his conclusions at the time, and did not allow him to report his findings until 1970.[51] [52]

In December 1977 the New York Academy of Sciences organized the first symposium on Chaos, attended by David Ruelle, Robert May, James A. Yorke (coiner of the term "chaos" as used in mathematics), Robert Shaw (a physicist, part of the Eudaemons group with J. Doyne Farmer and Norman Packard who tried to find a mathematical method to beat roulette, and then created with them the Dynamical Systems Collective in Santa Cruz, California), and the meteorologist Edward Lorenz.

The following year, Mitchell Feigenbaum published the noted article "Quantitative Universality for a Class of Nonlinear Transformations", where he described logistic maps.[53] Feigenbaum had applied fractal geometry to the study of natural forms such as coastlines. Feigenbaum notably discovered the universality in chaos, permitting an application of chaos theory to many different phenomena.

In 1979, Albert J. Libchaber, during a symposium organized in Aspen by Pierre Hohenberg, presented his experimental observation of the bifurcation cascade that leads to chaos and turbulence in convective Rayleigh–Benard systems. He was awarded the Wolf Prize in Physics in 1986 along with Mitchell J. Feigenbaum "for his brilliant experimental demonstration of the transition to turbulence and chaos in dynamical systems".[54]

Then in 1986 the New York Academy of Sciences co-organized with the National Institute of Mental Health and the Office of Naval Research the first important conference on Chaos in biology and medicine. There, Bernardo Huberman presented a mathematical model of the eye tracking disorder among schizophrenics.[55] This led to a renewal of physiology in the 1980s through the application of chaos theory, for example in the study of pathological cardiac cycles.

In 1987, Per Bak, Chao Tang and Kurt Wiesenfeld published a paper in *Physical Review Letters*[56] describing for the first time self-organized criticality (SOC), considered to be one of the mechanisms by which complexity arises in nature. Alongside largely lab-based approaches such as the Bak–Tang–Wiesenfeld sandpile, many other investigations have centered around large-scale natural or social systems that are known (or suspected) to display scale-invariant behaviour. Although these approaches were not always welcomed (at least initially) by specialists in the subjects examined, SOC has nevertheless become established as a strong candidate for explaining a number of natural phenomena, including: earthquakes (which, long before SOC was discovered, were known as a source of

scale-invariant behaviour such as the Gutenberg–Richter law describing the statistical distribution of earthquake sizes, and the Omori law[57] describing the frequency of aftershocks); solar flares; fluctuations in economic systems such as financial markets (references to SOC are common in econophysics); landscape formation; forest fires; landslides; epidemics; and biological evolution (where SOC has been invoked, for example, as the dynamical mechanism behind the theory of "punctuated equilibria" put forward by Niles Eldredge and Stephen Jay Gould). Worryingly, given the implications of a scale-free distribution of event sizes, some researchers have suggested that another phenomenon that should be considered an example of SOC is the occurrence of wars. These "applied" investigations of SOC have included both attempts at modelling (either developing new models or adapting existing ones to the specifics of a given natural system), and extensive data analysis to determine the existence and/or characteristics of natural scaling laws.

The same year, James Gleick published *Chaos: Making a New Science*, which became a best-seller and introduced the general principles of chaos theory as well as its history to the broad public. At first the domain of work of a few, isolated individuals, chaos theory progressively emerged as a transdisciplinary and institutional discipline, mainly under the name of nonlinear systems analysis. Alluding to Thomas Kuhn's concept of a paradigm shift exposed in *The Structure of Scientific Revolutions* (1962), many "chaologists" (as some self-nominated themselves) claimed that this new theory was an example of such a shift, a thesis upheld by J. Gleick.

The availability of cheaper, more powerful computers broadens the applicability of chaos theory. Currently, chaos theory continues to be a very active area of research, involving many different disciplines (mathematics, topology, physics, population biology, biology, meteorology, astrophysics, information theory, etc.).

Chaos theory is employed in everyday life in some microwave ovens, to aid rapid and (most notably) evenly-spread defrosting using microwave energy; this function is known as Chaos Defrost and was first developed by Panasonic in 2001.[58]

Distinguishing random from chaotic data

It can be difficult to tell from data whether a physical or other observed process is random or chaotic, because in practice no time series consists of pure 'signal.' There will always be some form of corrupting noise, even if it is present as round-off or truncation error. Thus any real time series, even if mostly deterministic, will contain some randomness.[59]

All methods for distinguishing deterministic and stochastic processes rely on the fact that a deterministic system always evolves in the same way from a given starting point.[59] [60] Thus, given a time series to test for determinism, one can:

1. pick a test state;
2. search the time series for a similar or 'nearby' state; and
3. compare their respective time evolutions.

Define the error as the difference between the time evolution of the 'test' state and the time evolution of the nearby state. A deterministic system will have an error that either remains small (stable, regular solution) or increases exponentially with time (chaos). A stochastic system will have a randomly distributed error.[61]

Essentially all measures of determinism taken from time series rely upon finding the closest states to a given 'test' state (i.e., correlation dimension, Lyapunov exponents, etc.). To define the state of a system one typically relies on phase space embedding methods.[62] Typically one chooses an embedding dimension, and investigates the propagation of the error between two nearby states. If the error looks random, one increases the dimension. If you can increase the dimension to obtain a deterministic looking error, then you are done. Though it may sound simple it is not really. One complication is that as the dimension increases the search for a nearby state requires a lot more computation time and a lot of data (the amount of data required increases exponentially with embedding dimension) to find a suitably close candidate. If the embedding dimension (number of measures per state) is chosen too small

(less than the 'true' value) deterministic data can appear to be random but in theory there is no problem choosing the dimension too large – the method will work.

When a non-linear deterministic system is attended by external fluctuations, its trajectories present serious and permanent distortions. Furthermore, the noise is amplified due to the inherent non-linearity and reveals totally new dynamical properties. Statistical tests attempting to separate noise from the deterministic skeleton or inversely isolate the deterministic part risk failure. Things become worse when the deterministic component is a non-linear feedback system.[63] In presence of interactions between nonlinear deterministic components and noise, the resulting nonlinear series can display dynamics that traditional tests for nonlinearity are sometimes not able to capture.[64]

Cultural references

Chaos theory has been mentioned in numerous novels and movies, such as *Jurassic Park*.

See also

Examples of chaotic systems

- Arnold's cat map
- Bouncing Ball Simulation System
- Chua's circuit
- Double pendulum
- Dynamical billiards
- Economic bubble
- Hénon map
- Horseshoe map
- Logistic map
- Rössler attractor
- Standard map
- Swinging Atwood's machine
- Tilt A Whirl
- Coupled map lattice
- List of chaotic maps

Other related topics

- Anosov diffeomorphism
- Bifurcation theory
- Butterfly effect
- Chaos theory in organizational development
- Complexity
- Control of chaos
- Edge of chaos
- Fractal
  - Julia set
  - Mandelbrot set
- Predictability
- Quantum chaos
- Santa Fe Institute
- Synchronization of chaos

People

- Mitchell Feigenbaum
- Martin Gutzwiller
- Michael Berry
- Brosl Hasslacher
- Michel Hénon
- Edward Lorenz
- Ian Malcolm
- Aleksandr Lyapunov
- Benoît Mandelbrot
- Henri Poincaré
- Otto Rössler
- David Ruelle
- Oleksandr Mikolaiovich Sharkovsky
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External links

- Nonlinear Dynamics Research Group [67] with Animations in Flash
- The Chaos group at the University of Maryland [68]
- The Chaos Hypertextbook [22]. An introductory primer on chaos and fractals.
- Society for Chaos Theory in Psychology & Life Sciences [69]
- Nonlinear Dynamics Research Group at CSDC [70], Florence Italy
- Interactive live chaotic pendulum experiment [71], allows users to interact and sample data from a real working damped driven chaotic pendulum
- Nonlinear dynamics: how science comprehends chaos [72], talk presented by Sunny Auyang, 1998.
- Nonlinear Dynamics [73]. Models of bifurcation and chaos by Elmer G. Wiens
- Gleick's *Chaos* (excerpt) [74]
- Systems Analysis, Modelling and Prediction Group [75] at the University of Oxford.
- A page about the Mackey-Glass equation [76].

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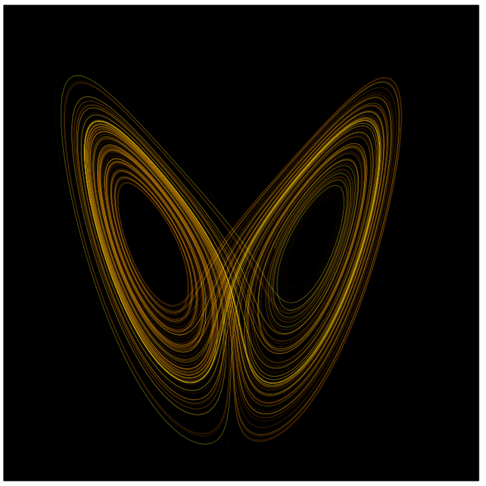
Lorentz attractor

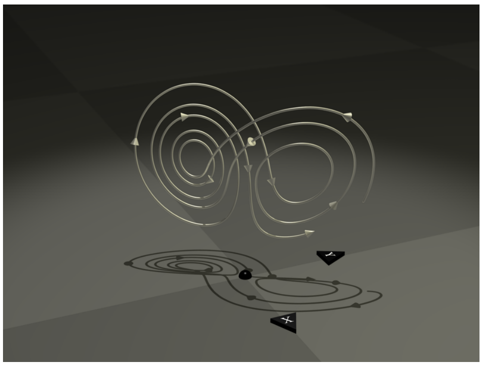
The **Lorenz attractor**, named for Edward N. Lorenz, is a fractal structure corresponding to the long-term behavior of the **Lorenz oscillator**. The Lorenz oscillator is a 3-dimensional dynamical system that exhibits chaotic flow, noted for its lemniscate shape. The map shows how the state of a dynamical system (the three variables of a three-dimensional system) evolves over time in a complex, non-repeating pattern.



A plot of the trajectory Lorenz system for values ρ=28, σ = 10, β = 8/3

Overview

The attractor itself, and the equations from which it is derived, were introduced by Edward Lorenz in 1963, who derived it from the simplified equations of convection rolls arising in the equations of the atmosphere.



A trajectory of Lorenz's equations, rendered as a metal wire to show direction and 3D structure

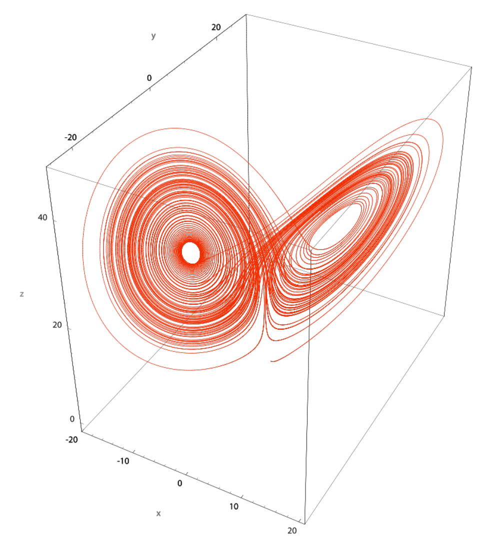
In addition to its interest to the field of non-linear mathematics, the Lorenz model has important implications for climate and weather prediction. The model is an explicit statement that planetary and stellar atmospheres may exhibit a variety of quasi-periodic regimes that are, although fully deterministic, subject to abrupt and seemingly random change.

From a technical standpoint, the Lorenz oscillator is nonlinear, three-dimensional and deterministic. In 2001 it was proven by Warwick Tucker that for a certain set of parameters the system exhibits chaotic behavior and displays what is today called a strange attractor. The strange attractor in this case is a fractal of Hausdorff dimension between 2 and 3. Grassberger (1983) has estimated the Hausdorff dimension to be 2.06 ± 0.01 and the correlation dimension to be 2.05 ± 0.01.

The system also arises in simplified models for lasers (Haken 1975) and dynamos (Knobloch 1981).

Equations

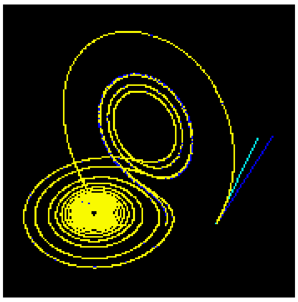
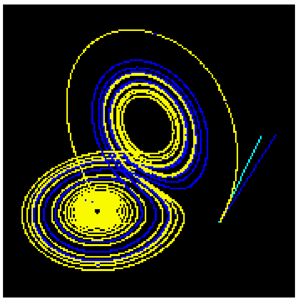
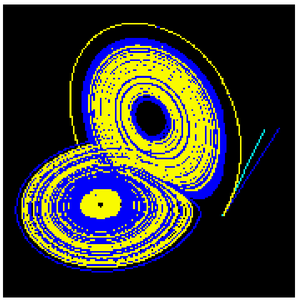
The equations that govern the Lorenz oscillator are:



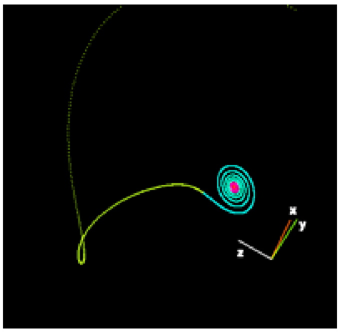
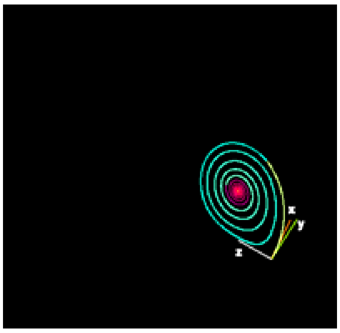
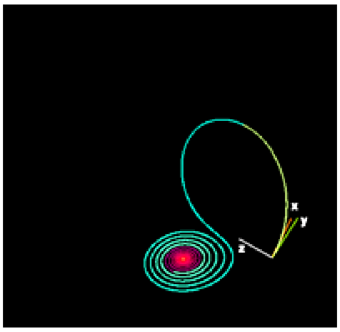
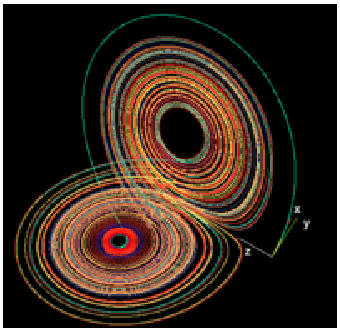
Trajectory with scales added

$$\frac{dx}{dt} = \sigma(y - x)$$
$$\frac{dy}{dt} = x(\rho - z) - y$$
$$\frac{dz}{dt} = xy - \beta z$$

where σ is called the **Prandtl number** and ρ is called the **Rayleigh number**. All σ , ρ, β > 0, but usually σ = 10, β = 8/3 and ρ is varied. The system exhibits chaotic behavior for ρ = 28 but displays knotted periodic orbits for other values of ρ. For example, with $\rho = 99.96$ it becomes a *T*(3,2) torus knot.

<table>
<tr><th colspan="3">Sensitive dependence on the initial condition</th></tr>
<tr><td>Time t=1 (Enlarge)</td><td>Time t=2 (Enlarge)</td><td>Time t=3 (Enlarge)</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td colspan="3">These figures — made using ρ=28, σ = 10 and β = 8/3 — show three time segments of the 3-D evolution of 2 trajectories (one in blue, the other in yellow) in the Lorenz attractor starting at two initial points that differ only by 10^{-5} in the x-coordinate. Initially, the two trajectories seem coincident (only the yellow one can be seen, as it is drawn over the blue one) but, after some time, the divergence is obvious.</td></tr>
<tr><td colspan="3">Java animation of the Lorenz attractor shows the continuous evolution. [6]</td></tr>
</table>

Rayleigh number

The Lorenz attractor for different values of ρ	
	
ρ=14, σ=10, β=8/3 (Enlarge)	**ρ=13, σ=10, β=8/3** (Enlarge)
	
ρ=15, σ=10, β=8/3 (Enlarge)	**ρ=28, σ=10, β=8/3** (Enlarge)
For small values of ρ, the system is stable and evolves to one of two fixed point attractors. When ρ is larger than 24.28, the fixed points become repulsors and the trajectory is repelled by them in a very complex way, evolving without ever crossing itself.	
Java animation showing evolution for different values of ρ [6]	

Source code

The source code to simulate the Lorenz attractor in GNU Octave follows.

```
## Lorenz Attractor equations solved by ODE Solve
## x' = sigma*(y-x)
## y' = x*(rho - z) - y
## z' = x*y - beta*z
function dx = lorenzatt(X)
    rho = 28; sigma = 10; beta = 8/3;
    dx = zeros(3,1);
    dx(1) = sigma*(X(2) - X(1));
    dx(2) = X(1)*(rho - X(3)) - X(2);
    dx(3) = X(1)*X(2) - beta*X(3);
    return
end
```

```
## Using LSODE to solve the ODE system.
clear all
close all
lsode_options("absolute tolerance",1e-3)
```

```
lsode_options("relative tolerance",1e-4)
t = linspace(0,25,1e3); X0 = [0,1,1.05];
[X,T,MSG]=lsode(@lorenzatt,X0,t);
T
MSG
plot3(X(:,1),X(:,2),X(:,3))
view(45,45)
```

See also

- List of chaotic maps
- Takens' theorem
- Mandelbrot set

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External links

- Weisstein, Eric W., "Lorenz attractor [4]" from MathWorld.
- Lorenz attractor [5] by Rob Morris, Wolfram Demonstrations Project.
- Lorenz equation [6] on planetmath.org
- For drawing the Lorenz attractor, or coping with a similar situation [7] using ANSI C and gnuplot.
- Synchronized Chaos and Private Communications, with Kevin Cuomo [8]. The implementation of Lorenz attractor in an electronic circuit.
- Lorenz attractor interactive animation [9] (you need the Adobe Shockwave plugin)
- Levitated.net: computational art and design [10]
- 3D Attractors: Mac program to visualize and explore the Lorenz attractor in 3 dimensions [11]
- 3D VRML Lorenz attractor [12] (you need a VRML viewer plugin)
- Essay on Lorenz attractors in J [13] - see J programming language
- Applet for non-linear simulations [14] (select "Lorenz attractor" preset), written by Viktor Bachraty in Jython
- Lorenz Attractor implemented in analog electronic [15]
- Visualizing the Lorenz attractor in 3D with Python and VTK [16]

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[3] http://www.math.uu.se/~warwick/main/rodes.html
[4] http://mathworld.wolfram.com/LorenzAttractor.html
[5] http://demonstrations.wolfram.com/LorenzAttractor/
[6] http://planetmath.org/encyclopedia/LorenzEquation.html
[7] http://www.mizuno.org/c/la/index.shtml
[8] http://video.google.com/videoplay?docid=2875296564158834562&q=strogatz&ei=xr9OSJ_SOpeG2wKB3Iy2DA&hl=en
[9] http://toxi.co.uk/lorenz/
[10] http://www.levitated.net/daily/levLorenzAttractor.html
[11] http://amath.colorado.edu/~juanga/3DAttractors.html
[12] http://ibiblio.org/e-notes/VRML/Lorenz/Lorenz.htm
[13] http://www.jsoftware.com/jwiki/Essays/Lorenz_Attractor
[14] http://student.fiit.stuba.sk/~bachratv02/mes/applet.html
[15] http://frank.harvard.edu/~paulh/misc/lorenz.htm
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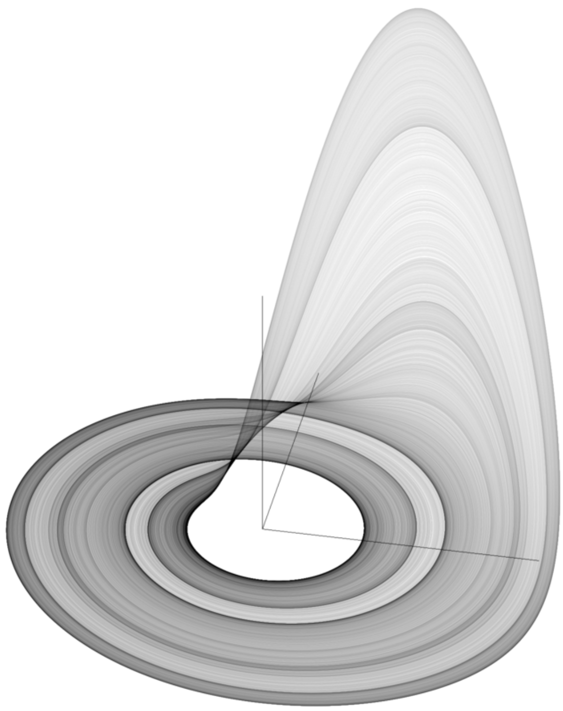
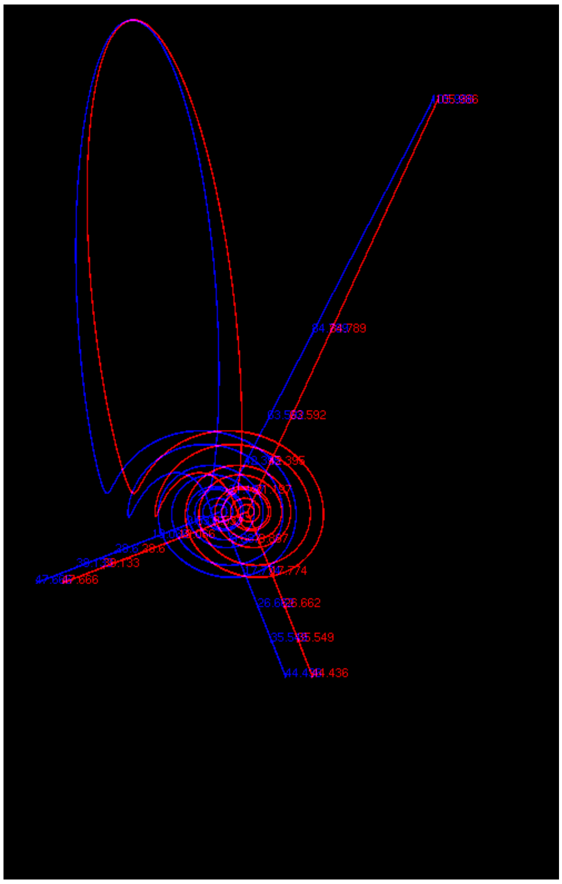
Rossler attractor



The Rössler attractor

The **Rössler attractor** (pronounced /ˈrɒslər/) is the attractor for the **Rössler system**, a system of three non-linear ordinary differential equations. These differential equations define a continuous-time dynamical system that exhibits chaotic dynamics associated with the fractal properties of the attractor. Some properties of the Rössler system can be deduced via linear methods such as eigenvectors, but the main features of the system require non-linear methods such as Poincaré maps and bifurcation diagrams. The original Rössler paper says the Rössler attractor was intended to behave similarly to the Lorenz attractor, but also be easier to analyze qualitatively. An orbit within the attractor follows an outward spiral close to the x, y plane around an unstable fixed point. Once the graph spirals out enough, a second fixed point influences the graph, causing a rise and twist in the z-dimension. In the time domain, it becomes apparent that although each variable is oscillating within a fixed range of values, the oscillations are chaotic. This attractor has some similarities to the Lorenz attractor, but is simpler and

has only one manifold. Otto Rössler designed the Rössler attractor in 1976, but the originally theoretical equations were later found to be useful in modeling equilibrium in chemical reactions. The defining equations are:



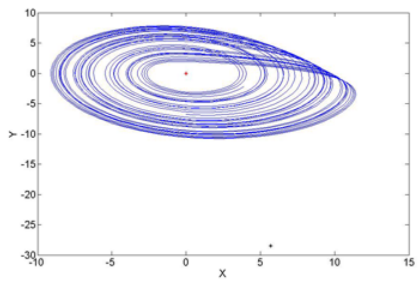
Rössler attractor as a stereogram with $a = 0.2$, $b = 0.2$, $c = 14$

$$\frac{dx}{dt} = -y - z$$
$$\frac{dy}{dt} = x + ay$$
$$\frac{dz}{dt} = b + z(x - c)$$

Rössler studied the chaotic attractor with $a = 0.2$, $b = 0.2$, and $c = 5.7$, though properties of $a = 0.1$, $b = 0.1$, and $c = 14$have been more commonly used since.

An analysis

Some of the Rössler attractor's elegance is due to two of its equations being linear; setting $z = 0$, allows examination of the behavior on the x, y plane



x, y plane of Rössler attractor with $a = 0.2$, $b = 0.2$, $c = 5.7$

$$\frac{dx}{dt} = -y$$
$$\frac{dy}{dt} = x + ay$$

The stability in the x, y plane can then be found by calculating the eigenvalues of the Jacobian $\begin{pmatrix} 0 & -1 \\ 1 & a \end{pmatrix}$, which are $(a \pm \sqrt{a^2 - 4})/2$. From this, we can see that when $0 < a < 2$, the eigenvalues are complex and at least one has a positive real component, making the origin unstable with an outwards spiral on the x, y plane. Now consider the z plane behavior within the context of this range for a. So long as x is smaller than c, the c term will keep the orbit close to the x, y plane. As the orbit approaches x greater than c, the z-values begin to climb. As z climbs, though, the $-z$ in the equation for dx/dt stops the growth in x.

Fixed points

In order to find the fixed points, the three Rössler equations are set to zero and the (x , y , z) coordinates of each fixed point were determined by solving the resulting equations. This yields the general equations of each of the fixed point coordinates:

$$x = \frac{c \pm \sqrt{c^2 - 4ab}}{2}$$
$$y = -\left(\frac{c \pm \sqrt{c^2 - 4ab}}{2a}\right)$$
$$z = \frac{c \pm \sqrt{c^2 - 4ab}}{2a}$$

Which in turn can be used to show the actual fixed points for a given set of parameter values:

$$\left(\frac{c + \sqrt{c^2 - 4ab}}{2}, \frac{-c - \sqrt{c^2 - 4ab}}{2a}, \frac{c + \sqrt{c^2 - 4ab}}{2a}\right)$$
$$\left(\frac{c - \sqrt{c^2 - 4ab}}{2}, \frac{-c + \sqrt{c^2 - 4ab}}{2a}, \frac{c - \sqrt{c^2 - 4ab}}{2a}\right)$$

As shown in the general plots of the Rössler Attractor above, one of these fixed points resides in the center of the attractor loop and the other lies comparatively removed from the attractor.

Eigenvalues and eigenvectors

The stability of each of these fixed points can be analyzed by determining their respective eigenvalues and eigenvectors. Beginning with the Jacobian:

$$\begin{pmatrix} 0 & -1 & -1 \\ 1 & a & 0 \\ z & 0 & x-c \end{pmatrix}$$

the eigenvalues can be determined by solving the following cubic:

$$-\lambda^3 + \lambda^2(a + x - c) + \lambda(ac - ax - 1 - z) + x - c + az = 0$$

For the centrally located fixed point, Rössler's original parameter values of a=0.2, b=0.2, and c=5.7 yield eigenvalues of:

$$\lambda_1 = 0.0971028 + 0.995786i$$
$$\lambda_2 = 0.0971028 - 0.995786i$$
$$\lambda_3 = -5.68718$$

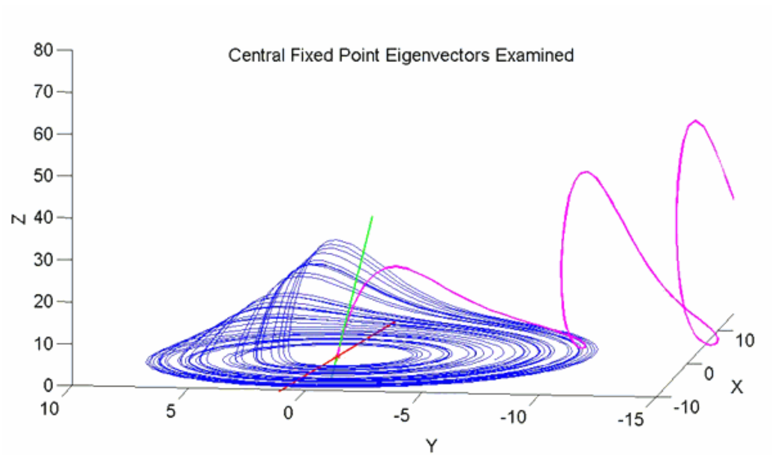
(Using Mathematica 7)

The magnitude of a negative eigenvalue characterizes the level of attraction along the corresponding eigenvector. Similarly the magnitude of a positive eigenvalue characterizes the level of repulsion along the corresponding eigenvector.

The eigenvectors corresponding to these eigenvalues are:

$$v_1 = \begin{pmatrix} 0.7073 \\ -0.07278 - 0.7032i \\ 0.0042 - 0.0007i \end{pmatrix}$$
$$v_2 = \begin{pmatrix} 0.7073 \\ 0.07278 + 0.7032i \\ 0.0042 + 0.0007i \end{pmatrix}$$
$$v_3 = \begin{pmatrix} 0.1682 \\ -0.0286 \\ 0.9853 \end{pmatrix}$$

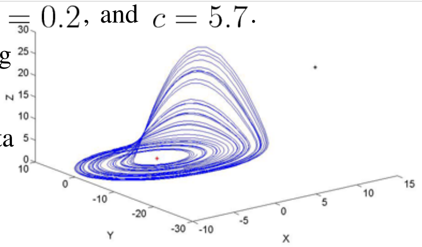
These eigenvectors have several interesting implications. First, the two eigenvalue/eigenvector pairs (v_1 and v_2) are responsible for the steady outward slide that occurs in the main disk of the attractor. The last eigenvalue/eigenvector pair is attracting along an axis that runs through the center of the manifold and accounts for the z motion that occurs within the attractor. This effect is roughly demonstrated with the figure below.



Examination of central fixed point eigenvectors: The blue line corresponds to the standard Rössler attractor generated with $a = 0.2$, $b = 0.2$, and $c = 5.7$.

The figure examines the central fixed point eigenvectors. The blue line

corresponds to the standard Rössler attractor generated with $a = 0.2$, $b = 0.2$, and $c = 5.7$. The red dot in the center of this attractor is FP_1. The red line intersecting that fixed point is an illustration of the repulsing plane generated by v_1 and v_2. The green line is an illustration of the attracting v_3. The magenta line is generated by stepping backwards through time from a point on the attracting eigenvector which is slightly above FP_1 – it illustrates the behavior of points that become completely dominated by that vector. Note that the magenta line nearly touches the plane of the attractor before being pulled upwards into the fixed point; this suggests that the general appearance and behavior of the Rössler attractor is largely a product of the interaction between the attracting v_3 and the repelling v_1 and v_2 plane. Specifically it implies that a sequence generated from the Rössler equations will begin to loop around FP_1, start being pulled upwards into the v_3 vector, creating the upward arm of a curve that bends slightly inward toward the vector before being pushed outward again as it is pulled back towards the repelling plane.



Rössler attractor with $a = 0.2$, $b = 0.2$, $c = 5.7$

For the outlier fixed point, Rössler's original parameter values of $a = 0.2$, $b = 0.2$, and $c = 5.7$ yield eigenvalues of:

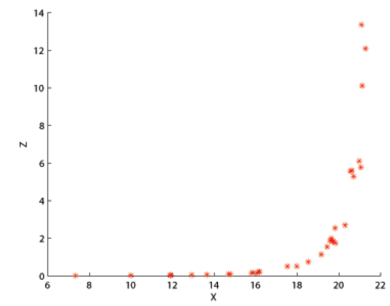
$$\lambda_1 = -0.0000046 + 5.4280259i$$
$$\lambda_2 = -0.0000046 - 5.4280259i$$
$$\lambda_3 = 0.1929830$$

The eigenvectors corresponding to these eigenvalues are:

$$v_1 = \begin{pmatrix} 0.0002422 + 0.1872055i \\ 0.0344403 - 0.0013136i \\ 0.9817159 \end{pmatrix}$$
$$v_2 = \begin{pmatrix} 0.0002422 - 0.1872055i \\ 0.0344403 + 0.0013136i \\ 0.9817159 \end{pmatrix}$$
$$v_3 = \begin{pmatrix} 0.0049651 \\ -0.7075770 \\ 0.7066188 \end{pmatrix}$$

Although these eigenvalues and eigenvectors exist in the Rössler attractor, their influence is confined to iterations of the Rössler system whose initial conditions are in the general vicinity of this outlier fixed point. Except in those cases where the initial conditions lie on the attracting plane generated by λ_1 and λ_2, this influence effectively involves pushing the resulting system towards the general Rössler attractor. As the resulting sequence approaches the central fixed point and the attractor itself, the influence of this distant fixed point (and its eigenvectors) will wane.

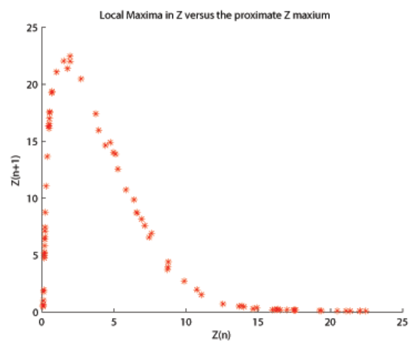
Poincaré map



Poincaré map for Rössler attractor with $a = 0.1$, $b = 0.1$, $c = 14$

The Poincaré map is constructed by plotting the value of the function every time it passes through a set plane in a specific direction. An example would be plotting the y, z value every time it passes through the $x = 0$ plane where x is changing from negative to positive, commonly done when studying the Lorenz attractor. In the case of the Rössler attractor, the $x = 0$ plane is uninteresting, as the map always crosses the $x = 0$ plane at $z = 0$ due to the nature of the Rössler equations. In the $a = 0.1$ plane for $a = 0.1$, $b = 0.1$, $c = 14$, the Poincaré map shows the upswing in z values as x increases, as is to be expected due to the upswing and twist section of the Rössler plot. The number of points in this specific Poincaré plot is infinite, but when a different c value is used, the number of points can vary. For example, with a c value of 4, there is only one point on the Poincaré map, because the function yields a periodic orbit of period one, or if the c value is set to 12.8, there would be six points corresponding to a period six orbit.

Mapping local maxima



Z_n vs. Z_{n+1}

In the original paper on the Lorenz Attractor, Edward Lorenz analyzed the local maxima of z against the immediately preceding local maxima. When visualized, the plot resembled the tent map, implying that similar analysis can be used between the map and attractor. For the Rössler attractor, when the z_n local maximum is plotted against the next local z maximum, z_{n+1}, the resulting plot (shown here for $a = 0.2$, $b = 0.2$, $c = 5.7$) is unimodal, resembling a skewed Henon map. Knowing that the Rössler attractor can be used to create a pseudo 1-d map, it then follows to use similar analysis methods. The bifurcation diagram is specifically a useful analysis method.

Variation of parameters

Rössler attractor's behavior is largely a factor of the values of its constant parameters (a , b , and c). In general varying each parameter has a comparable effect by causing the system to converge toward a periodic orbit, fixed point, or escape towards infinity, however the specific ranges and behaviors induced vary substantially for each parameter. Periodic orbits, or "unit cycles," of the Rössler system are defined by the number of loops around the central point that occur before the loops series begins to repeat itself.

Bifurcation diagrams are a common tool for analyzing the behavior of chaotic systems. Bifurcation diagrams for the Rössler attractor are created by iterating through the Rössler ODEs holding two of the parameters constant while conducting a parameter sweep over a range of possible values for the third. The local x maxima for each varying parameter value is then plotted against that parameter value. These maxima are determined after the attractor has reached steady state and any initial transient behaviors have disappeared. This is useful in determining the relationship between periodicity and the selected parameter. Increasing numbers of points in a vertical line on a bifurcation diagram indicates the Rössler attractor behaves chaotically that value of the parameter being examined.

Varying a

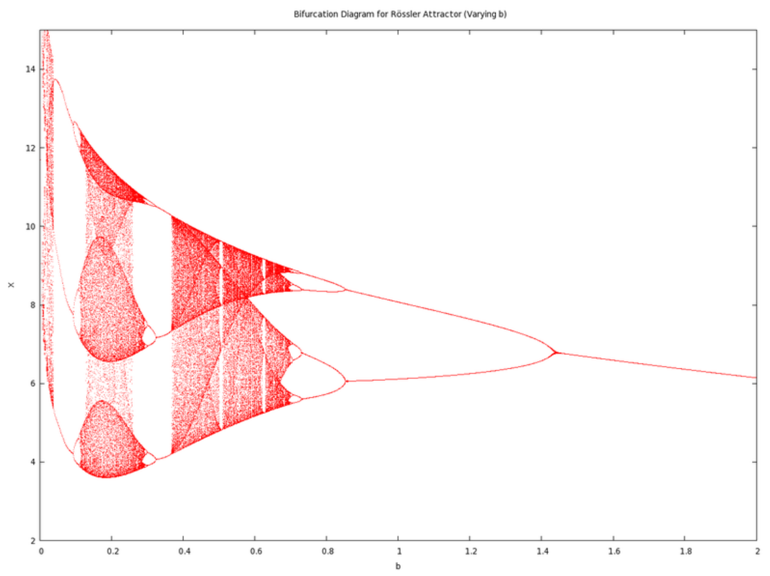
In order to examine the behavior of the Rössler attractor for different values of a , b was fixed at 0.2, c was fixed at 5.7. Numerical examination of attractor's behavior over changing a suggests it has a disproportional influence over the attractor's behavior. Some examples of this relationship include:

- $a \leq 0$: converges to the centrally located fixed point
- $a = 0.1$: unit cycle of period 1
- $a = 0.2$: standard parameter value selected by Rössler, chaotic
- $a = 0.3$: chaotic attractor, significantly more Möbius strip-like (folding over itself).
- $a = 0.35$: similar to .3, but increasingly chaotic
- $a = 0.38$: similar to .35, but increasingly chaotic

If a gets even slightly larger than .38, it causes MATLAB to hang. Note this suggests that the practical range of a is very narrow.

Varying b

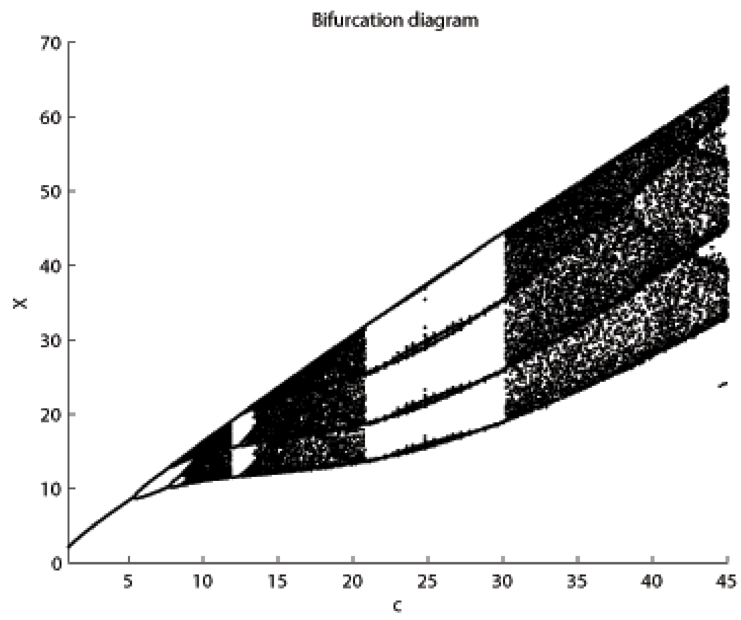
The effect of b on the Rössler attractor's behavior is best illustrated through a bifurcation diagram. This bifurcation diagram was created with $a = 0.2$, $c = 5.7$. As shown in the accompanying diagram, as b approaches 0 the attractor approaches infinity (note the upswing for very small values of b . Comparative to the other parameters, varying b seems to generate a greater range when period-3 and period-6 orbits will occur. In contrast to a and c , higher values of b systems that converge on a period-1 orbit instead of higher level orbits or chaotic attractors.



Bifurcation diagram for the Rössler attractor for varying b

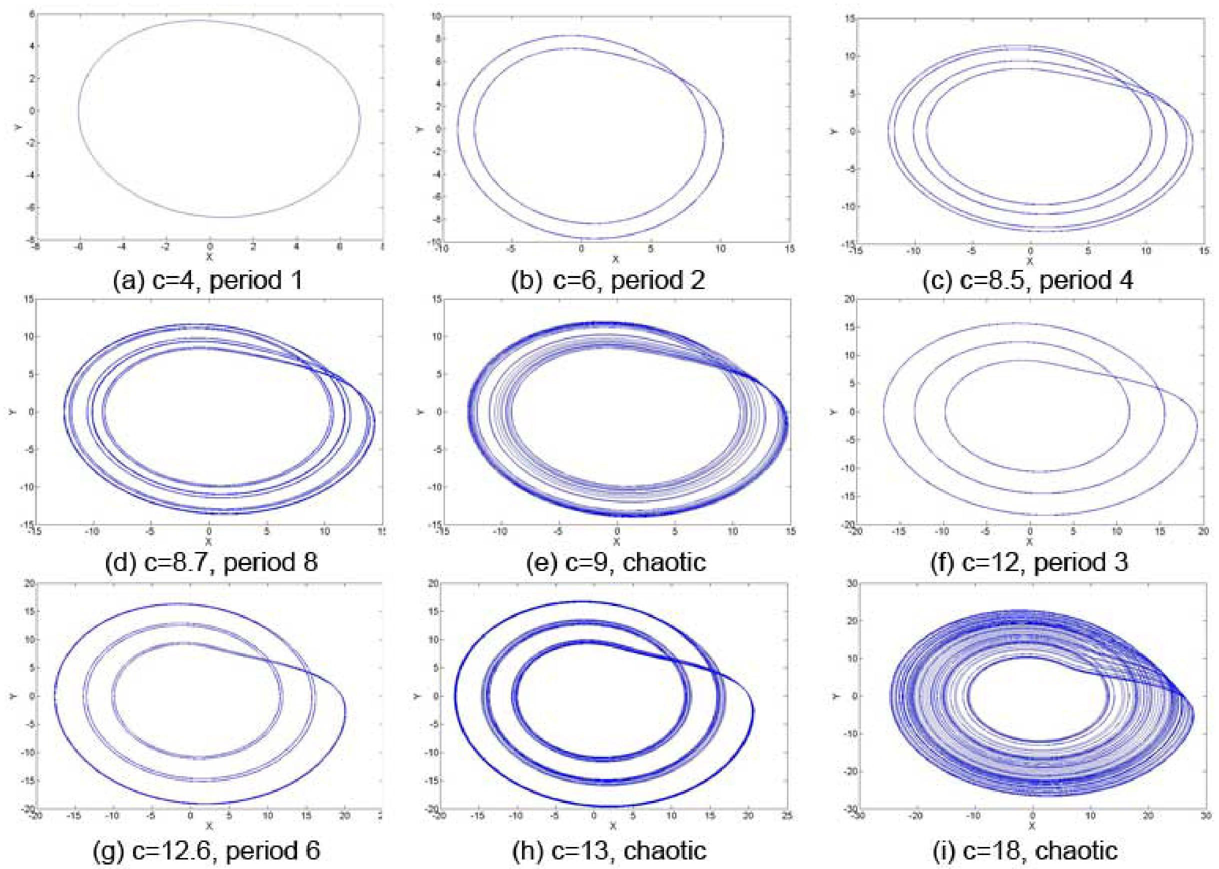
Varying c

The traditional bifurcation diagram for the Rössler attractor is created by varying c with $a = b = .1$. This bifurcation diagram reveals that low values of c are periodic, but quickly become chaotic as c increases. This pattern repeats itself as c increases – there are sections of periodicity interspersed with periods of chaos, although the trend is towards higher order periodic orbits in the periodic sections as c increases. For example, the period one orbit only appears for values of c around 4 and is never found again in the bifurcation diagram. The same phenomena is seen with period three; until $c = 12$, period three orbits can be found, but thereafter, they do not appear.



Bifurcation diagram for the Rössler attractor for varying c

A graphical illustration of the changing attractor over a range of c values illustrates the general behavior seen for all of these parameter analyses – the frequent transitions from ranges of relative stability and periodicity to completely chaotic and back again.



The above set of images illustrates the variations in the post-transient Rössler system as c is varied over a range of values. These images were generated with $a = b = .1$ (a) $c = 4$, periodic orbit. (b) $c = 6$, period-2 orbit. (c) $c = 8.5$, period-4 orbit. (d) $c = 8.7$, period-8 orbit. (e) $c = 9$, sparse chaotic attractor. (f) $c = 12$, period-3 orbit. (g) $c = 12.6$, period-6 orbit. (h) $c = 13$, sparse chaotic attractor. (i) $c = 18$, filled-in chaotic attractor.

Links to other topics

The banding evident in the Rössler attractor is similar to a Cantor set rotated about its midpoint. Additionally, the half-twist in the Rössler attractor makes it similar to a Möbius strip.

See also

- Lorenz attractor
- List of chaotic maps
- Chaos theory
- Dynamical system
- Fractals
- Otto Rössler

References

- E. N. Lorenz (1963). "Deterministic nonperiodic flow". *J. Atmos. Sci.* **20**: 130–141. doi:10.1175/1520-0469(1963)020<0130:DNF>2.0.CO;2.
- O. E. Rössler (1976). "An Equation for Continuous Chaos". *Physics Letters* **57A** (5): 397–398.
- O. E. Rössler (1979). "An Equation for Hyperchaos". *Physics Letters* **71A** (2,3): 155–157.
- Steven H. Strogatz (1994). *Nonlinear Dynamics and Chaos*. Perseus publishing.

External links

- Flash Animation using PovRay [1]
- Lorenz and Rössler attractors [6] – Java animation
- Java 3D interactive Rössler attractor [2]
- 3D Attractors: Mac program to visualize and explore the Rössler and Lorenz attractors in 3 dimensions [11]
- Rössler attractor in Scholarpedia [3]

References

[1] http://lagrange.physics.drexel.edu/flash/rossray
[2] http://mrmartin.net/code/RosslerAttractor.html
[3] http://scholarpedia.org/article/Rossler_attractor

List of chaotic maps

In mathematics, a **chaotic map** is a map that exhibits some sort of chaotic behavior. Maps may be parameterized by a discrete-time or a continuous-time parameter. Discrete maps usually take the form of iterated functions. Chaotic maps often occur in the study of dynamical systems.

Chaotic maps often generate fractals. Although a fractal may be constructed by an iterative procedure, some fractals are studied in and of themselves, as sets rather than in terms of the map that generates them. This is often because there are several different iterative procedures to generate the same fractal.

List of chaotic maps

Map	Time domain	Space domain	Number of space dimensions	Also known as
Arnold's cat map	discrete	real	2	
Baker's map	discrete	real	2	
Bogdanov map				
Chossat-Golubitsky symmetry map				
Circle map	discrete	real	1	
Cob Web map				
Complex quadratic map	discrete	complex	1	
Complex squaring map	discrete	complex	1	
Complex Cubic map				
Degenerate Double Rotor map				
Double Rotor map				
Duffing map	discrete	real	2	
Duffing equation	continuous	real	1	
Dyadic transformation	discrete	real	1	2x mod 1 map, Bernoulli map, doubling map, sawtooth map
Exponential map	discrete	complex	2	
Gauss map	discrete	real	1	mouse map, Gaussian map
Generalized Baker map				
Gingerbreadman map	discrete	real	2	
Gumowski/Mira map				
Hénon map	discrete	real	2	
Hénon with 5th order polynomial				
Hitzl-Zele map				
Horseshoe map	discrete	real	2	
Ikeda map	discrete	real	2	
Interval exchange map	discrete	real	1	
Kaplan-Yorke map	discrete	real	2	
Linear map on unit square				

Logistic map	discrete	real	1	
Lorenz attractor	continuous	real	3	
Lorenz system's Poincare Return map				
Lozi map				
Nordmark truncated map				
Pomeau-Manneville maps for intermittent chaos	discrete	real	1 and 2	Normal-form maps for intermittency (Types I, II and III)
Pulsed Rotor & standard map				
Quasiperiodicity map				
Rabinovich-Fabrikant equations	continuous	real	3	
Random Rotate map				
Rössler map	continuous	real	3	
Shobu-Ose-Mori piecewise-linear map	discrete	real	1	piecewise-linear approximation for Pomeau-Manneville Type I map
Sinai map - See [1]				
Symplectic map				
Standard map	discrete	real	2	Chirikov standard map, Chirikov-Taylor map
Tangent map				
Tent map	discrete	real	1	
Tinkerbell map	discrete	real	2	
Triangle map				
Van der Pol oscillator	continuous	real	1	
Zaslavskii map	discrete	real	2	
Zaslavskii rotation map				

List of fractals

- Cantor set
- Gravity set, or Mitchell-Green gravity set
- Julia set - derived from complex quadratic map
- Koch snowflake
- Lyapunov fractal
- Mandelbrot set - derived from complex quadratic map
- Menger sponge
- Sierpinski carpet
- Sierpinski triangle

References

[1] http://www.maths.ox.ac.uk/~mcsharry/papers/dynsys18n3p191y2003mcsharry.pdf

Other Applications

Social network

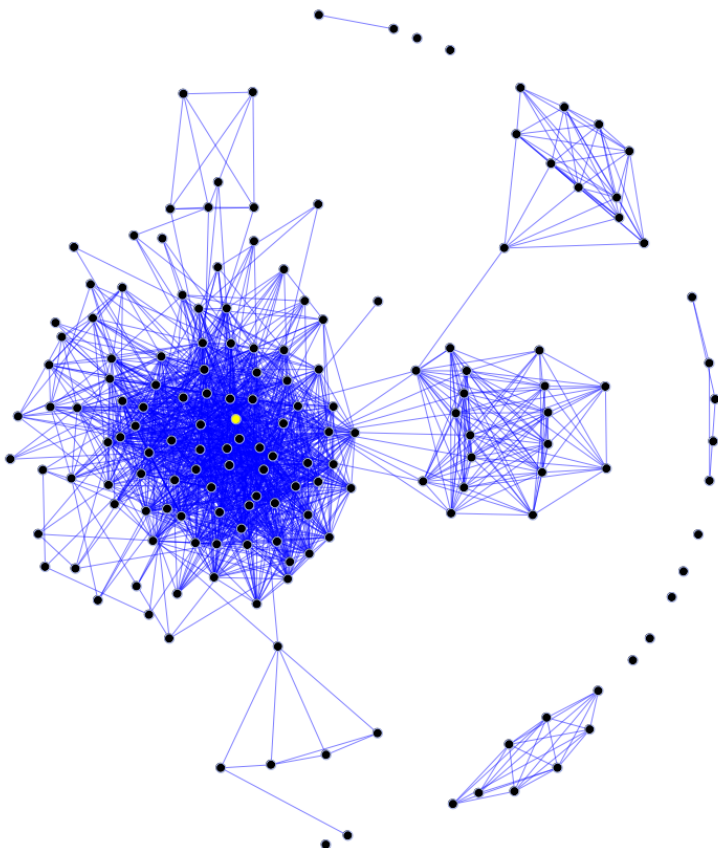
A **social network** is a social structure made of individuals (or organizations) called "nodes," which are tied (connected) by one or more specific types of interdependency, such as friendship, kinship, financial exchange, dislike, sexual relationships, or relationships of beliefs, knowledge or prestige.

Social network analysis views social relationships in terms of network theory consisting of *nodes* and *ties*. Nodes are the individual actors within the networks, and ties are the relationships between the actors. The resulting graph-based structures are often very complex. There can be many kinds of ties between the nodes. Research in a number of academic fields has shown that social networks operate on many levels, from families up to the level of nations, and play a critical role in determining the way problems are solved, organizations are run, and the degree to which individuals succeed in achieving their goals.

In its simplest form, a social network is a map of all of the relevant ties between all the nodes being studied. The network can also be used to measure social capital -- the value that an individual gets from the social network. These concepts are often displayed in a social network diagram, where nodes are the points and ties are the lines.

Social network analysis

Social network analysis (related to *network theory*) has emerged as a key technique in modern sociology. It has also gained a significant following in anthropology, biology, communication studies, economics, geography, information science, organizational studies, social psychology, and sociolinguistics, and has become a popular topic of speculation and study.



An example of a social network diagram. The node with the highest betweenness centrality is marked in yellow.

People have used the idea of **"social network"** loosely for over a century to connote complex sets of relationships between members of social systems at all scales, from interpersonal to international. In 1954, J. A. Barnes started using the term systematically to denote patterns of ties, encompassing concepts traditionally used by the public and those used by social scientists: bounded groups (e.g., tribes, families) and social categories (e.g., gender, ethnicity). Scholars such as S.D. Berkowitz, Stephen Borgatti, Ronald Burt, Kathleen Carley, Martin Everett, Katherine Faust,

Linton Freeman, Mark Granovetter, David Knoke, David Krackhardt, Peter Marsden, Nicholas Mullins, Anatol Rapoport, Stanley Wasserman, Barry Wellman, Douglas R. White, and Harrison White expanded the use of systematic social network analysis.[1]

Social network analysis has now moved from being a suggestive metaphor to an analytic approach to a paradigm, with its own theoretical statements, methods, social network analysis software, and researchers. Analysts reason from whole to part; from structure to relation to individual; from behavior to attitude. They typically either study *whole networks* (also known as *complete networks*), all of the ties containing specified relations in a defined population, or *personal networks* (also known as *egocentric networks*), the ties that specified people have, such as their "personal communities".[2] The distinction between whole/complete networks and personal/egocentric networks has depended largely on how analysts were able to gather data. That is, for groups such as companies, schools, or membership societies, the analyst was expected to have complete information about who was in the network, all participants being both potential egos and alters. Personal/egocentric studies were typically conducted when identities of egos were known, but not their alters. These studies rely on the egos to provide information about the identities of alters and there is no expectation that the various egos or sets of alters will be tied to each other. A *snowball network* refers to the idea that the alters identified in an egocentric survey then become egos themselves and are able in turn to nominate additional alters. While there are severe logistic limits to conducting snowball network studies, a method for examining *hybrid networks* has recently been developed in which egos in complete networks can nominate alters otherwise not listed who are then available for all subsequent egos to see. [3] The hybrid network may be valuable for examining whole/complete networks that are expected to include important players beyond those who are formally identified. For example, employees of a company often work with non-company consultants who may be part of a network that cannot fully be defined prior to data collection.

Several analytic tendencies distinguish social network analysis:[4]

- There is no assumption that groups are the building blocks of society: the approach is open to studying less-bounded social systems, from nonlocal communities to links among websites.
- Rather than treating individuals (persons, organizations, states) as discrete units of analysis, it focuses on how the structure of ties affects individuals and their relationships.
- In contrast to analyses that assume that socialization into norms determines behavior, network analysis looks to see the extent to which the structure and composition of ties affect norms.

The shape of a social network helps determine a network's usefulness to its individuals. Smaller, tighter networks can be less useful to their members than networks with lots of loose connections (weak ties) to individuals outside the main network. More open networks, with many weak ties and social connections, are more likely to introduce new ideas and opportunities to their members than closed networks with many redundant ties. In other words, a group of friends who only do things with each other already share the same knowledge and opportunities. A group of individuals with connections to other social worlds is likely to have access to a wider range of information. It is better for individual success to have connections to a variety of networks rather than many connections within a single network. Similarly, individuals can exercise influence or act as brokers within their social networks by bridging two networks that are not directly linked (called filling structural holes).[5]

The power of social network analysis stems from its difference from traditional social scientific studies, which assume that it is the attributes of individual actors—whether they are friendly or unfriendly, smart or dumb, etc.—that matter. Social network analysis produces an alternate view, where the attributes of individuals are less important than their relationships and ties with other actors within the network. This approach has turned out to be useful for explaining many real-world phenomena, but leaves less room for individual agency, the ability for individuals to influence their success, because so much of it rests within the structure of their network.

Social networks have also been used to examine how organizations interact with each other, characterizing the many informal connections that link executives together, as well as associations and connections between individual employees at different organizations. For example, power within organizations often comes more from the degree to

which an individual within a network is at the center of many relationships than actual job title. Social networks also play a key role in hiring, in business success, and in job performance. Networks provide ways for companies to gather information, deter competition, and collude in setting prices or policies.[6]

History of social network analysis

A summary of the progress of social networks and social network analysis has been written by Linton Freeman.[7]

Precursors of social networks in the late 1800s include Émile Durkheim and Ferdinand Tönnies. Tönnies argued that social groups can exist as personal and direct social ties that either link individuals who share values and belief (*gemeinschaft*) or impersonal, formal, and instrumental social links (*gesellschaft*). Durkheim gave a non-individualistic explanation of social facts arguing that social phenomena arise when interacting individuals constitute a reality that can no longer be accounted for in terms of the properties of individual actors. He distinguished between a traditional society – "mechanical solidarity" – which prevails if individual differences are minimized, and the modern society – "organic solidarity" – that develops out of cooperation between differentiated individuals with independent roles.

Georg Simmel, writing at the turn of the twentieth century, was the first scholar to think directly in social network terms. His essays pointed to the nature of network size on interaction and to the likelihood of interaction in ramified, loosely-knit networks rather than groups (Simmel, 1908/1971).

After a hiatus in the first decades of the twentieth century, three main traditions in social networks appeared. In the 1930s, J.L. Moreno pioneered the systematic recording and analysis of social interaction in small groups, especially classrooms and work groups (sociometry), while a Harvard group led by W. Lloyd Warner and Elton Mayo explored interpersonal relations at work. In 1940, A.R. Radcliffe-Brown's presidential address to British anthropologists urged the systematic study of networks.[8] However, it took about 15 years before this call was followed-up systematically.

Social network analysis developed with the kinship studies of Elizabeth Bott in England in the 1950s and the 1950s-1960s urbanization studies of the University of Manchester group of anthropologists (centered around Max Gluckman and later J. Clyde Mitchell) investigating community networks in southern Africa, India and the United Kingdom. Concomitantly, British anthropologist S.F. Nadel codified a theory of social structure that was influential in later network analysis.[9]

In the 1960s-1970s, a growing number of scholars worked to combine the different tracks and traditions. One group was centered around Harrison White and his students at the Harvard University Department of Social Relations: Ivan Chase, Bonnie Erickson, Harriet Friedmann, Mark Granovetter, Nancy Howell, Joel Levine, Nicholas Mullins, John Padgett, Michael Schwartz and Barry Wellman. Also important in this early group were Charles Tilly, who focused on networks in political sociology and social movements, and Stanley Milgram, who developed the "six degrees of separation" thesis.[10] Mark Granovetter and Barry Wellman are among the former students of White who have elaborated and popularized social network analysis.[11]

White's was not the only group. Significant independent work was done by scholars elsewhere: University of California Irvine social scientists interested in mathematical applications, centered around Linton Freeman, including John Boyd, Susan Freeman, Kathryn Faust, A. Kimball Romney and Douglas White; quantitative analysts at the University of Chicago, including Joseph Galaskiewicz, Wendy Griswold, Edward Laumann, Peter Marsden, Martina Morris, and John Padgett; and communication scholars at Michigan State University, including Nan Lin and Everett Rogers. A substantively-oriented University of Toronto sociology group developed in the 1970s, centered on former students of Harrison White: S.D. Berkowitz, Harriet Friedmann, Nancy Leslie Howard, Nancy Howell, Lorne Tepperman and Barry Wellman, and also including noted modeler and game theorist Anatol Rapoport.In terms of theory, it critiqued methodological individualism and group-based analyses, arguing that seeing the world as social networks offered more analytic leverage.[12]

Research

Social network analysis has been used in epidemiology to help understand how patterns of human contact aid or inhibit the spread of diseases such as HIV in a population. The evolution of social networks can sometimes be modeled by the use of agent based models, providing insight into the interplay between communication rules, rumor spreading and social structure.

SNA may also be an effective tool for mass surveillance -- for example the Total Information Awareness program was doing in-depth research on strategies to analyze social networks to determine whether or not U.S. citizens were political threats.

Diffusion of innovations theory explores social networks and their role in influencing the spread of new ideas and practices. Change agents and opinion leaders often play major roles in spurring the adoption of innovations, although factors inherent to the innovations also play a role.

Robin Dunbar has suggested that the typical size of a egocentric network is constrained to about 150 members due to possible limits in the capacity of the human communication channel. The rule arises from cross-cultural studies in sociology and especially anthropology of the maximum size of a village (in modern parlance most reasonably understood as an *ecovillage*). It is theorized in evolutionary psychology that the number may be some kind of limit of average human ability to recognize members and track emotional facts about all members of a group. However, it may be due to economics and the need to track "free riders", as it may be easier in larger groups to take advantage of the benefits of living in a community without contributing to those benefits.

Mark Granovetter found in one study that more numerous weak ties can be important in seeking information and innovation. Cliques have a tendency to have more homogeneous opinions as well as share many common traits. This homophilic tendency was the reason for the members of the cliques to be attracted together in the first place. However, being similar, each member of the clique would also know more or less what the other members knew. To find new information or insights, members of the clique will have to look beyond the clique to its other friends and acquaintances. This is what Granovetter called "the strength of weak ties".

Guanxi is a central concept in Chinese society (and other East Asian cultures) that can be summarized as the use of personal influence. Guanxi can be studied from a social network approach.[13]

The small world phenomenon is the hypothesis that the chain of social acquaintances required to connect one arbitrary person to another arbitrary person anywhere in the world is generally short. The concept gave rise to the famous phrase six degrees of separation after a 1967 *small world experiment* by psychologist Stanley Milgram. In Milgram's experiment, a sample of US individuals were asked to reach a particular target person by passing a message along a chain of acquaintances. The average length of successful chains turned out to be about five intermediaries or six separation steps (the majority of chains in that study actually failed to complete). The methods (and ethics as well) of Milgram's experiment was later questioned by an American scholar, and some further research to replicate Milgram's findings had found that the degrees of connection needed could be higher.[14] Academic researchers continue to explore this phenomenon as Internet-based communication technology has supplemented the phone and postal systems available during the times of Milgram. A recent electronic small world experiment at Columbia University found that about five to seven degrees of separation are sufficient for connecting any two people through e-mail.[15]

Collaboration graphs can be used to illustrate good and bad relationships between humans. A positive edge between two nodes denotes a positive relationship (friendship, alliance, dating) and a negative edge between two nodes denotes a negative relationship (hatred, anger). Signed social network graphs can be used to predict the future evolution of the graph. In signed social networks, there is the concept of "balanced" and "unbalanced" cycles. A balanced cycle is defined as a cycle where the product of all the signs are positive. Balanced graphs represent a group of people who are unlikely to change their opinions of the other people in the group. Unbalanced graphs represent a group of people who are very likely to change their opinions of the people in their group. For example, a

group of 3 people (A, B, and C) where A and B have a positive relationship, B and C have a positive relationship, but C and A have a negative relationship is an unbalanced cycle. This group is very likely to morph into a balanced cycle, such as one where B only has a good relationship with A, and both A and B have a negative relationship with C. By using the concept of balances and unbalanced cycles, the evolution of signed social network graphs can be predicted.

One study has found that happiness tends to be correlated in social networks. When a person is happy, nearby friends have a 25 percent higher chance of being happy themselves. Furthermore, people at the center of a social network tend to become happier in the future than those at the periphery. Clusters of happy and unhappy people were discerned within the studied networks, with a reach of three degrees of separation: a person's happiness was associated with the level of happiness of their friends' friends' friends.[16]

Some researchers have suggested that human social networks may have a genetic basis.[17] Using a sample of twins from the National Longitudinal Study of Adolescent Health, they found that in-degree (the number of times a person is named as a friend), transitivity (the probability that two friends are friends with one another), and betweenness centrality (the number of paths in the network that pass through a given person) are all significantly heritable. Existing models of network formation cannot account for this intrinsic node variation, so the researchers propose an alternative "Attract and Introduce" model that can explain heritability and many other features of human social networks.[18]

Application to Environmental Issues

The 1984 book The IRG Solution argued that central media and government-type hierarchical organizations could not adequately understand the environmental crisis we were manufacturing, or how to initiate adequate solutions. It argued that the widespread introduction of Information Routing Groups was required to create a social network whose overall intelligence could collectively understand the issues and devise and implement correct workeable solutions and policies.

Metrics (Measures) in social network analysis

Betweenness

> The extent to which a node lies between other nodes in the network. This measure takes into account the connectivity of the node's neighbors, giving a higher value for nodes which bridge clusters. The measure reflects the number of people who a person is connecting indirectly through their direct links.[19]

Bridge

> An edge is said to be a bridge if deleting it would cause its endpoints to lie in different components of a graph.

Centrality

> This measure gives a rough indication of the social power of a node based on how well they "connect" the network. "Betweenness", "Closeness", and "Degree" are all measures of centrality.

Centralization

> The difference between the number of links for each node divided by maximum possible sum of differences. A centralized network will have many of its links dispersed around one or a few nodes, while a decentralized network is one in which there is little variation between the number of links each node possesses.

Closeness

> The degree an individual is near all other individuals in a network (directly or indirectly). It reflects the ability to access information through the "grapevine" of network members. Thus, closeness is the inverse of the sum of the shortest distances between each individual and every other person in the network. (See also: Proxemics) The shortest path may also be known as the "geodesic distance".

Clustering coefficient

A measure of the likelihood that two associates of a node are associates themselves. A higher clustering coefficient indicates a greater 'cliquishness'.

Cohesion

The degree to which actors are connected directly to each other by cohesive bonds. Groups are identified as ‘cliques’ if every individual is directly tied to every other individual, ‘social circles’ if there is less stringency of direct contact, which is imprecise, or as structurally cohesive blocks if precision is wanted.[20]

Degree

The count of the number of ties to other actors in the network. See also degree (graph theory).

(Individual-level) Density

The degree a respondent's ties know one another/ proportion of ties among an individual's nominees. Network or global-level density is the proportion of ties in a network relative to the total number possible (sparse versus dense networks).

Flow betweenness centrality

The degree that a node contributes to sum of maximum flow between all pairs of nodes (not that node).

Eigenvector centrality

A measure of the importance of a node in a network. It assigns relative scores to all nodes in the network based on the principle that connections to nodes having a high score contribute more to the score of the node in question.

Local Bridge

An edge is a local bridge if its endpoints share no common neighbors. Unlike a bridge, a local bridge is contained in a cycle.

Path Length

The distances between pairs of nodes in the network. Average path-length is the average of these distances between all pairs of nodes.

Prestige

In a directed graph prestige is the term used to describe a node's centrality. "Degree Prestige", "Proximity Prestige", and "Status Prestige" are all measures of Prestige. See also degree (graph theory).

Radiality

Degree an individual’s network reaches out into the network and provides novel information and influence.

Reach

The degree any member of a network can reach other members of the network.

Structural cohesion

The minimum number of members who, if removed from a group, would disconnect the group.[21]

Structural equivalence

Refers to the extent to which nodes have a common set of linkages to other nodes in the system. The nodes don’t need to have any ties to each other to be structurally equivalent.

Structural hole

Static holes that can be strategically filled by connecting one or more links to link together other points. Linked to ideas of social capital: if you link to two people who are not linked you can control their communication.

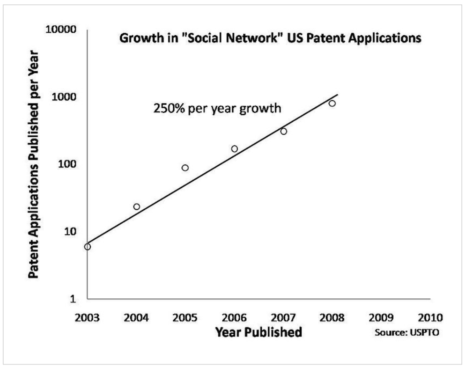
Network analytic software

Network analytic tools are used to represent the nodes (agents) and edges (relationships) in a network, and to analyze the network data. Like other software tools, the data can be saved in external files. Additional information comparing the various data input formats used by network analysis software packages is available at NetWiki. Network analysis tools allow researchers to investigate large networks like the Internet, disease transmission, etc. These tools provide mathematical functions that can be applied to the network model.

Visual representation of social networks is important to understand the network data and convey the result of the analysis [22]. Network analysis tools are used to change the layout, colors, size and advanced properties of the network representation.

Patents

There has been rapid growth in the number of US patent applications that cover new technologies related to social networking. The number of published applications has been growing at about 250% per year over the past five years. There are now over 2000 published applications. [23] Only about 100 of these applications have issued as patents, however, largely due to the multi-year backlog in examination of business method patents and ethical issues connected with this patent category [24]



See also

- Clique
- Community of practice
- Dynamic network analysis
- Digital footprint
- FOAF (software) (Friend of a friend)
- Friendship paradox
- Knowledge management
- List of social networking websites
- Mathematical sociology
- Metcalfe's Law
- Network analysis
- Network of practice
- Network science
- Organizational patterns
- Small world phenomenon
- Social-circles network model
- Social networking service
- Social network aggregation
- Social network analysis software
- Social software
- Social unit
- Social web
- SocialRank
- Socio-technical systems
- Surveillance
- Triadic closure
- Value network
- Virtual community
- Virtual organization
- Weighted network

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External links

- The International Network for Social Network Analysis [35] (INSNA) - professional society of social network analysts, with more than 1,000 members
- Annual International Workshop on Social Network Mining and Analysis [36] SNAKDD - Annual computer science workshop for interdisciplinary studies on social network mining and analysis
- VisualComplexity.com [37] - a visual exploration on mapping complicated and complex networks
- Center for Computational Analysis of Social and Organizational Systems (CASOS) at Carnegie Mellon [38]
- NetLab at the University of Toronto, studies the intersection of social, communication, information and computing networks [39]
- Netwiki [6] (wiki page devoted to social networks; maintained at University of North Carolina at Chapel Hill)
- Building networks for learning [40]- A guide to on-line resources on strengthening social networking.
- Program on Networked Governance [41] - Program on Networked Governance, Harvard University

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Sociology and complexity science

Sociology and complexity science (also referred to as sociology and complexity) is a new area of study within the larger field of complexity science—its acronym is SACS.[1] [2] [3] SACS formally emerged around 1998, when sociologists and social scientists made what John Urry refers to as the complexity science turn; that is, the critical integration of the tools of complexity science (e.g., agent-based modeling, the new science of networks, etc) into the social sciences.[4]

Historically speaking, SACS is part of the systems tradition (systems thinking) within sociology. The systems tradition within sociology has three basic phases: (1) the classical era (late 1800s to 1920s), which included such scholars as Karl Marx, Max Weber, Vilfredo Pareto, Herbert Spencer and Emile Durkheim; (2) the prewar era (1940s to 1960s), which revolved around the work of Talcott Parsons and Robert Merton; and (3) the complexity turn era (1990s to present).[5] [6]

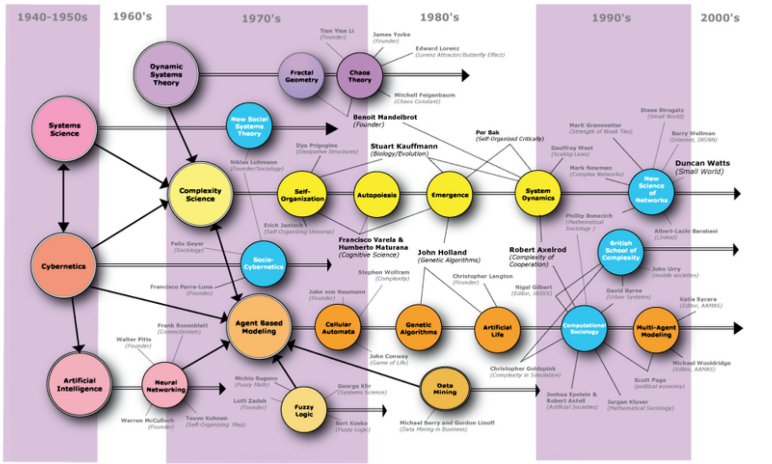
Scholars involved include Duncan Watts, Albert-László Barabási, Mark Newman, Immanuel Wallerstein, Manuel Castells, John Urry and Nigel Gilbert the creator and editor of the *Journal of Artificial Societies and Social Simulation* and a pioneer of computational sociology.

While the substantive topics addresses by the scholars of SACS are numerous, there is a common focus. In one way or another, the overarching focus is on social complexity and social systems. Social systems are alternatively referred to as complex systems, complex adaptive systems or complex social systems.

The SACS comprises five areas of research: (1) computational sociology, (2) the British-based School of Complexity (See John Urry (sociologist)) , (3) the Luhmann School of Complexity (see Niklas Luhmann), (4) sociocybernetics and, finally, (5) complex social network analysis (See complex network, social network and network society). Associated areas are complex organizations (see complexity theory and organizations), web science, e-social science (see e-science), computational economics, and computational political science.

Historical background

An argument can be made that western sociology (including its various smaller, national sociologies) has been and continues to be a profession of complexity.[8] [9] The primary basis for this challenge is western society. To study society is, by definition, to study complexity. Starting with the industrial and "industrious" revolutions of the middle 1700s to early 1900s western society transitioned—teleology not implied—into a type of complexity that, in many ways, did not previously exist. Furthermore, as industrialization evolved into its later stages (i.e., Taylorism, Fordism, post-Fordism, etc), the complexity of western society evolved as well (See Arnold J. Toynbee). The latest developments in this complexity are post-industrialism and, most recently, across societies throughout the world, globalization.



'A perspective on, and partial map of Complexity Science. The web version [7] lists links to academics and research.

Classical era

Of the numerous scholars writing during the middle 1800s to early 1900s, perhaps the best known systems thinkers were Auguste Comte, Herbert Spencer, Karl Marx, Max Weber, Emile Durkheim and Vilfredo Pareto. While not all of these scholars were sociologists, their systems thinking had a tremendous impact on organized sociology. Three characteristics identify these scholars as systems thinkers: (1) They conceptualized their work as a direct response to the increasing complexity of western society; (2) they conceptualized the changes taking place in western society in systems terms; that is, they treated western society (and its various substantive issues) as a system; and (3) their failure and successes show scholars today how best to think about social complexity in systems terms. Their failures include treating social systems in strictly biological terms--homeostasis, etc. Their successes include Pareto's 80/20 rule and Durkheim's notion of system differentiation (sociology).

the postwar era

The postwar era in sociological systems thinking was influenced by Talcott Parsons action theory and, to a lesser extent by the work of Robert Merton. Parsons developed a theory of society and social evolution through a volunataristic methodology. is famous for his baroque theory of systems, known as structural functionalism. While Parsons theory developed an advance approach to the differentiational complexity of society, which forshadowed the development of complexity science and, more specifically, SACS, in two important ways.[10] First, it foreshadowed SACS insomuch as it integrated sociological inquiry with systems science. While Parsons grounded his theory in a hierarchy of theoretical complexity in which classical socoiology was one, cybernetic and approaches within cognitive and biological science was others. In retrospect both system theory and cybernetics and be interpreted as precursors to complexity science.[11] Second, through his development of the *Department of Social Relations* at *Harvard,* Parsons foreshadowed the trans-disciplinary, center-based orientation of complexity science--from the Santa Fe Institute to the Centre for Research in Social Simulation [12]. Parsons sought to create an international, post-disciplinary, highly mobile community of scholars devoted to integrating sociology and systems thinking to enhance sociological inquiry.

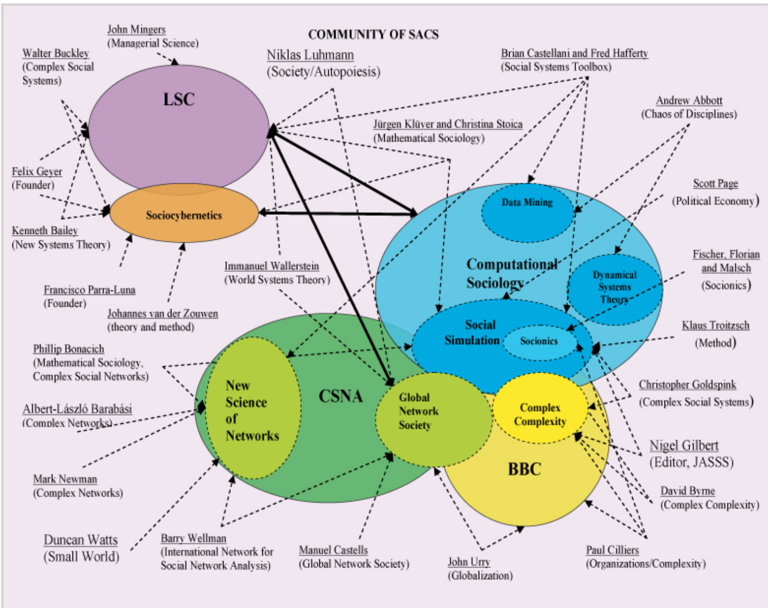
Complexity turn era

The community of SACS is part of what John Urry (2005) calls the *complexity turn* in the social sciences. As Urry explains, most of the work being done within the SACS community got its start in the late 1990s, around the same time that complexity science was finally gaining international recognition; thanks, in large measure, to the growing prestige of the Santa Fe Institute (Santa Fe, New Mexico, USA), the birthplace of complexity science.[13] During the late 1990s, the scholars of SACS were spread out across Western Europe and North America, working (for the most part) in intellectual and geographical isolation from one another, pursuing diverse areas of study that, at the time, seemed hardly related. In the late 1990s, these areas included: (1) computational sociology, (2) complex social network analysis, (3) sociocybernetics,(4) the Luhmann School of Complexity, and, (5) the British-based School of Complexity (BBC).[14] The agenda basically was an exegetical restoration of the twin goals of Talcott Parsons: (a) thinking about the growing complexity of global society in systems terms and (b) integrating sociology with the latest advances in complexity science.

Areas of research in SACS

Complex Social Network Analysis

The goal of complex social network analysis (CSNA) is to study the dynamics of large, complex networks such as the internet (web science), global diseases, and corporate interactions. Through the usage of key concepts and methods in social network analysis, agent-based modeling, theoretical physics, and modern mathematics (particularly graph theory and fractal geometry), this field of inquiry has made some astonishing insights into the dynamics and structure of social systems (i.e., small-world phenomenon, scale-free networks, etc.). This area of research has two subclusters: the new science of networks and global network society. The former primarily emerges out of the work of Duncan Watts and colleagues, while the latter (which overlaps with the British-based School of Complexity) primarily emerges out of the work of John Urry and the sociological study of globalization. The latter also comes from the work of Manuel Castells and the later work of Immanuel Wallerstein which, since 1998, increasingly makes use of complexity science, particularly the work of Ilya Prigogine.[16] [17] [18]



'**Map 2: Map of Sociology and Complexity Science**. *HERE FOR WEB VERSION OF MAP [15]

Computational Sociology

The second area is computational sociology involving such scholars as Nigel Gilbert, Klaus Troitzsch, Scott Page, Joshua Epstein and Jürgen Klüver--see Map 2 for information on these scholars. The focus of researchers in this field, amount to two: social simulation and data-mining, both of which are subclusters within computational sociology. Social simulation uses the computer to create an artificial laboratory for the study of complex social systems, and data-mining uses machine intelligence to search for non-trivial patterns of relations in large, complex,

real-world databases. A variant of computational sociology is socionics. [19] [20]

Luhmann School of Complexity

The third field, and the one most different from the first two in terms of epistemology and method, is the Luhmann School of Complexity (LSC). Based primarily upon the work of Niklas Luhmann, the goal of this school of thought (which is very developed in Germany) is to reinvigorate the study of society as a complex social system. In this way, this perspective can be read as an attempt to succeed where Parsons failed, primarily by relying upon the latest advances in systems science and cybernetics, which are the same two fields Parsons drew upon to do his work.[21] [22] [23]

Sociocybernetics

The fourth major area of research is sociocybernetics. The main goal of this field is to integrate sociology with second-order cybernetics and Niklas Luhmann, along with the latest advances in complexity science. In terms of scholarly work, the focus of sociocybernetics has been primarily conceptual and only slightly methodological or empirical.[24]

British-based School of Complexity

The final area of research is the British-based School of Complexity (BBC), a small but growing school of thought.[25] [26] While the above four areas seek to make major advances in the discipline of sociology, the BBC is attempting to go further. They are not just interested in revising or advancing the current practice of sociology. They seek to reformulate the theories, concepts, methods and organizational arrangements of sociology through the employment of complexity science.[27] A school of thought is a defined way of doing scholarly work, based on the teachings or instructions of a particular group of scholars. In the case of the BBC, the main scholars are David Byrne, John Urry, and Nigel Gilbert. The work being done through these scholars' writing include (1) establishing agent-based modeling as a legitimate form of sociological inquiry (which the BBC is doing through its work with computational sociology, specifically Nigel Gilbert);[28] (2) problematizing the heavy numerical orientation of mainstream complexity science by developing a qualitative-based, fuzzy-logic approach[29] [30] (including the application of this work to the study of health and health care and urban environments); [31] [32] (3) constructing a mobile sociology based on the latest advances in network and globalization theory; [33] [34] and (4) creating a number of innovative organizational arrangements, including the development of interdisciplinary centers, departments, conferences and associations devoted to the study of social complexity.[35] When put together, all of this amounts to a new school of thinking in sociology, albeit not as developed yet as the Luhmann School of Complexity.

See also

- Complex adaptive system
- Complexity
- Complexity economics
- Computational sociology
- Generative sciences
- Multi-agent system
- Social network analysis
- Sociocybernetics
- Systems theory

External links

- Sociology and Complexity Science Website [36]
- Castellani and Hafferty (2009) Sociology and Complexity Science: A New Area of Inquiry [37]
- SOCIOLOGY AND COMPLEXITY SCIENCE BLOG: An Educational Tool for Researchers and Students [38]
- On-line book "Simulation for the Social Scientist" by Nigel Gilbert and Klaus G. Troitzsch, 1999, second edition 2005 [39]
- Journal of Artificial Societies and Social Simulation [40]
- From Factors to Actors: Computational Sociology and Agent-based Modeling - Review by Michael Macy and Robert Willer [41]

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Sociocybernetics

Sociocybernetics is an independent chapter of science in sociology based upon the General Systems Theory and cybernetics.

It also has a basis in Organizational Development (OD) consultancy practice and in Theories of Communication, theories of psychotherapies and computer sciences. The International Sociological Association has a specialist research committee in the area – RC51 [1] – which publishes the (electronic) *Journal of Sociocybernetics*.

The term "socio" in the name of sociocybernetics refers to any social system (as defined, among others, by Talcott Parsons and Niklas Luhmann).

The idea to study society as a system can be traced back to the origin of sociology when the emergent idea of functional differentiation has been applied for the first time to society by Auguste Comte.

The basic goal for which sociocybernetics was created, is the production of a theoretical framework as well as information technology tools for responding to the basic challenges individuals, couples, families, groups, companies, organizations, countries, international affairs are facing today.

Sociocybernetics analyzes social 'forces'

One of the tasks of sociocybernetics is to map, measure, harness, and find ways of intervening in the parallel network of social forces that influence human behavior. Sociocyberneticists' task is to understand the guidance and control mechanisms that govern the operation of society (and the behavior of individuals more generally) in practice and then to devise better ways of harnessing and intervening in them – that is to say to devise more effective ways to operate these mechanisms, or to modify them according to the opinions of the cyberneticist.

Sociocybernetics aims to generate a general theoretical framework for understanding cooperative behavior.

It claims to give a deep understanding of the General Theory of Evolution. The outlook that Sociocybernetics uses when analyzing any living system lies in a Basic Law of SocioCybernetics. It says: All living systems go through five levels of interrelations (social contracts) of its subsystems:

- A. Aggression: survive or die
- B. Bureaucracy: follow the norms and rules
- C. Competition: my gain is your loss
- D. Decision: disclosing individual feelings, intentions
- E. Empathy: cooperation in one unified interest

Going through these five phases of relationship theoretically gives the framework for the sociocybernetic study of any evolutionary system. It serves as an "equation for life."

Issues and challenges

Recent research from the Santa Fe Institute presents the idea that social systems like cities don't behave like organisms as has been proposed by some in sociocybernetics.[2]

Perhaps the most basic challenges faced by sociocyberneticians are those that stem from Bookchin's work "The Ecology of Freedom and the emergence and decline of Hierarchy".

Bookchin's argument is that what have often been described as "primitive" societies are best thought of as "organic" societies. People within them have differentiated roles as do the cells of a body, but this differentiation is largely reversible. Coordination between the cells is not organized by some "center" but through a network of feedback (cybernetic) processes. Particularly important are organisms' ability to evolve as well as reproduce. But simply saying that the process is "autopoietic" is to evade the task of identifying the multiple and mutually reinforcing cybernetic processes that are at work.

Yet Bookchin's claim, which appears to be thoroughly documented, is that the evolution of organic societies into our current, vastly destructive, hierarchical societies - *over millennia* - has also taken place through some ... (almost cancerous?) ... unstoppable autopoietic process. If we are to halt this process ... which is about to destroy us as a species, probably carrying the planet as we know it with us, it will be necessary to map and find ways of intervening in the sociocybernetic processes involved. No centralised system-wide, command-and-control oriented, change will suffice. Systems intervention requires complex systems-oriented intervention targeted at nodes in the system, not system-wide change based on "common sense".

See also

- Anthropology
- Cliodynamics
- Complex systems
- Dynastic cycle
- General systems theory
- List of cycles
- Psychology
- Social cycle theory
- Sociology
- Superorganisms
- Systems philosophy
- Systems thinking
- War cycles
- World-systems theory

Further reading

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External links

- Center for Sociocybernetics Studies Bonn [6]

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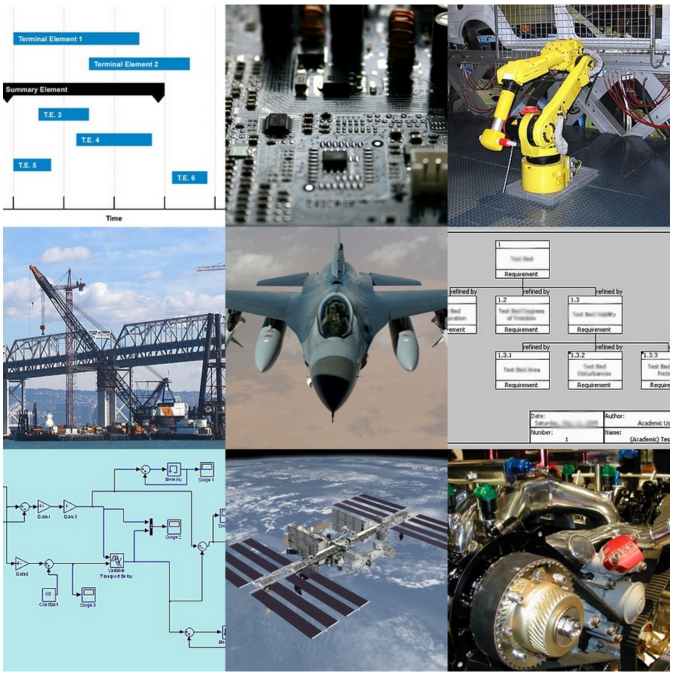
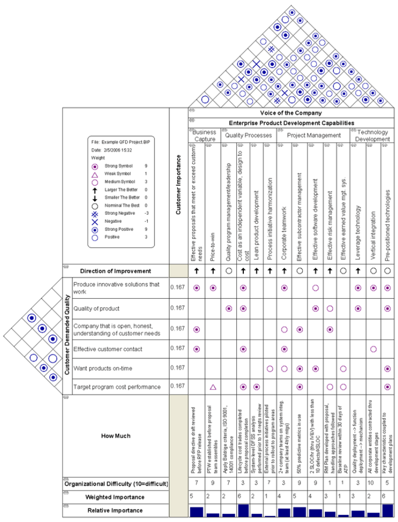
Systems engineering

Systems engineering is an interdisciplinary field of engineering that focuses on how complex engineering projects should be designed and managed. Issues such as logistics, the coordination of different teams, and automatic control of machinery become more difficult when dealing with large, complex projects. Systems engineering deals with work-processes and tools to handle such projects, and it overlaps with both technical and human-centered disciplines such as control engineering and project management.



Systems engineering techniques are used in complex projects: spacecraft design, computer chip design, robotics, software integration, and bridge building. Systems engineering uses a host of tools that include modeling and simulation, requirements analysis and scheduling to manage complexity.

History



QFD House of Quality for Enterprise Product Development Processes

The term *systems engineering* can be traced back to Bell Telephone Laboratories in the 1940s.[1] The need to identify and manipulate the properties of a system as a whole, which in complex engineering projects may greatly differ from the sum of the parts' properties, motivated the Department of Defense, NASA, and other industries to apply the discipline.[2]

When it was no longer possible to rely on design evolution to improve upon a system and the existing tools were not sufficient to meet growing demands, new methods began to be developed that addressed the complexity directly.[3] The evolution of systems engineering, which continues to this day, comprises the development and identification of new methods and modeling techniques. These methods aid in better comprehension of engineering systems as they grow more complex. Popular tools that are often used in the Systems Engineering context were developed during these times, including USL, UML, QFD, and IDEF0.

In 1990, a professional society for systems engineering, the *National Council on Systems Engineering* (NCOSE), was founded by representatives from a number of US corporations and organizations. NCOSE was created to address the need for improvements in systems engineering practices and education. As a result of growing involvement from systems engineers outside of the U.S., the name of the organization was changed to the International Council on Systems Engineering (INCOSE) in 1995.[4] Schools in several countries offer graduate programs in systems engineering, and continuing education options are also available for practicing engineers.[5]

Concept

Some definitions

"An interdisciplinary approach and means to enable the realization of successful systems"[6] — *INCOSE handbook, 2004.*

"System engineering is a robust approach to the design, creation, and operation of systems. In simple terms, the approach consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals."[7] — *NASA Systems engineering handbook, 1995.*

"The Art and Science of creating effective systems, using whole system, whole life principles" OR "The Art and Science of creating optimal solution systems to complex issues and problems"[8] — *Derek Hitchins, Prof. of Systems Engineering, former president of INCOSE (UK), 2007.*

"The concept from the engineering standpoint is the evolution of the engineering scientist, i.e., the scientific generalist who maintains a broad outlook. The method is that of the team approach. On large-scale-system problems, teams of scientists and engineers, generalists as well as specialists, exert their joint efforts to find a solution and physically realize it...The technique has been variously called the systems approach or the team development method."[9] — *Harry H. Goode & Robert E. Machol, 1957.*

"The Systems Engineering method recognizes each system is an integrated whole even though composed of diverse, specialized structures and sub-functions. It further recognizes that any system has a number of objectives and that the balance between them may differ widely from system to system. The methods seek to optimize the overall system functions according to the weighted objectives and

to achieve maximum compatibility of its parts."[10] — *Systems Engineering Tools by Harold Chestnut, 1965.*

Systems Engineering signifies both an approach and, more recently, as a discipline in engineering. The aim of education in Systems Engineering is to simply formalize the approach and in doing so, identify new methods and research opportunities similar to the way it occurs in other fields of engineering. As an approach, Systems Engineering is holistic and interdisciplinary in flavor.

Origins and traditional scope

The traditional scope of engineering embraces the design, development, production and operation of physical systems, and systems engineering, as originally conceived, falls within this scope. "Systems engineering", in this sense of the term, refers to the distinctive set of concepts, methodologies, organizational structures (and so on) that have been developed to meet the challenges of engineering functional physical systems of unprecedented complexity. The Apollo program is a leading example of a systems engineering project.

The use of the term "systems engineering" has evolved over time to embrace a wider, more holistic concept of "systems" and of engineering processes. This evolution of the definition has been a subject of ongoing controversy [11], and the term continues to be applied to both the narrower and broader scope.

Holistic view

Systems Engineering focuses on analyzing and eliciting customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem, the system lifecycle. Oliver *et al.* claim that the systems engineering process can be decomposed into

- a *Systems Engineering Technical Process*, and
- a *Systems Engineering Management Process*.

Within Oliver's model, the goal of the Management Process is to organize the technical effort in the lifecycle, while the Technical Process includes *assessing available information*, *defining effectiveness measures*, to *create a behavior model*, *create a structure model*, *perform trade-off analysis*, and *create sequential build & test plan*.[12]

Depending on their application, although there are several models that are used in the industry, all of them aim to identify the relation between the various stages mentioned above and incorporate feedback. Examples of such models include the Waterfall model and the VEE model.[13]

Interdisciplinary field

System development often requires contribution from diverse technical disciplines.[14] By providing a systems (holistic) view of the development effort, systems engineering helps meld all the technical contributors into a unified team effort, forming a structured development process that proceeds from concept to production to operation and, in some cases, to termination and disposal.

This perspective is often replicated in educational programs in that Systems Engineering courses are taught by faculty from other engineering departments which, in effect, helps create an interdisciplinary environment.[15] [16]

Managing complexity

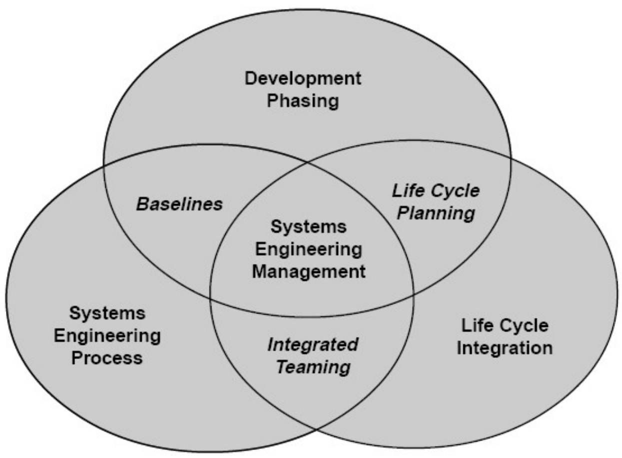
The need for systems engineering arose with the increase in complexity of systems and projects. When speaking in this context, complexity incorporates not only engineering systems, but also the logical human organization of data. At the same time, a system can become more complex due to an increase in size as well as with an increase in the amount of data, variables, or the number of fields that are involved in the design. The International Space Station is an example of such a system.

The development of smarter control algorithms, microprocessor design, and analysis of environmental systems also come within the purview of systems engineering. Systems engineering encourages the use of tools and methods to better comprehend and manage complexity in systems. Some examples of these tools can be seen here:[17]

- *Modeling and Simulation*,
- *Optimization*,
- *System dynamics*,
- *Systems analysis*,
- *Statistical analysis*,
- *Reliability analysis*, and
- *Decision making*

Taking an interdisciplinary approach to engineering systems is inherently complex since the behavior of and interaction among system components is not always immediately well defined or understood. Defining and characterizing such systems and subsystems and the interactions among them is one of the goals of systems engineering. In doing so, the gap that exists between informal requirements from users, operators, marketing organizations, and technical specifications is successfully bridged.

Scope



The scope of Systems Engineering activities[18]

One way to understand the motivation behind systems engineering is to see it as a method, or practice, to identify and improve common rules that exist within a wide variety of systems. Keeping this in mind, the principles of Systems Engineering — holism, emergent behavior, boundary, et al. — can be applied to any system, complex or otherwise, provided systems thinking is employed at all levels.[19] Besides defense and aerospace, many information and technology based companies, software development firms, and industries in the field of electronics & communications require Systems engineers as part of their team.[20]

An analysis by the INCOSE Systems Engineering center of excellence (SECOE) indicates that optimal effort spent on Systems Engineering is about 15-20% of the total project effort.[21] At the same time, studies have shown that Systems Engineering essentially leads to reduction in costs among other benefits.[21] However, no quantitative survey at a larger scale encompassing a wide variety of industries has been conducted until recently. Such studies are underway to determine the effectiveness and quantify the benefits of Systems engineering.[22] [23]

Systems engineering encourages the use of modeling and simulation to validate assumptions or theories on systems and the interactions within them.[24] [25]

Use of methods that allow early detection of possible failures, in Safety engineering, are integrated into the design process. At the same time, decisions made at the beginning of a project whose consequences are not clearly understood can have enormous implications later in the life of a system, and it is the task of the modern systems

engineer to explore these issues and make critical decisions. There is no method which guarantees that decisions made today will still be valid when a system goes into service years or decades after it is first conceived but there are techniques to support the process of systems engineering. Examples include the use of soft systems methodology, Jay Wright Forrester's System dynamics method and the Unified Modeling Language (UML), each of which are currently being explored, evaluated and developed to support the engineering decision making process.

Education

Education in systems engineering is often seen as an extension to the regular engineering courses,[26] reflecting the industry attitude that engineering students need a foundational background in one of the traditional engineering disciplines (e.g. mechanical engineering, industrial engineering, computer science, electrical engineering) plus practical, real-world experience in order to be effective as systems engineers. Undergraduate university programs in systems engineering are rare.

INCOSE maintains a continuously updated Directory of Systems Engineering Academic Programs worldwide.[5] As of 2006, there are about 75 institutions in United States that offer 130 undergraduate and graduate programs in systems engineering. Education in systems engineering can be taken as *SE-centric* or *Domain-centric*.

- *SE-centric* programs treat systems engineering as a separate discipline and all the courses are taught focusing on systems engineering practice and techniques.
- *Domain-centric* programs offer systems engineering as an option that can be exercised with another major field in engineering.

Both these patterns cater to educate the systems engineer who is able to oversee interdisciplinary projects with the depth required of a core-engineer.[27]

Systems engineering topics

Systems engineering tools are strategies, procedures, and techniques that aid in performing systems engineering on a project or product. The purpose of these tools vary from database management, graphical browsing, simulation, and reasoning, to document production, neutral import/export and more.[28]

System

There are many definitions of what a system is in the field of systems engineering. Below are a few authoritative definitions:

- ANSI/EIA-632-1999: "An aggregation of end products and enabling products to achieve a given purpose."[29]
- IEEE Std 1220-1998: "A set or arrangement of elements and processes that are related and whose behavior satisfies customer/operational needs and provides for life cycle sustainment of the products."[30]
- ISO/IEC 15288:2008: "A combination of interacting elements organized to achieve one or more stated purposes."[31]
- NASA Systems Engineering Handbook: "(1) The combination of elements that function together to produce the capability to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for this purpose. (2) The end product (which performs operational functions) and enabling products (which provide life-cycle support services to the operational end products) that make up a system."[32]
- INCOSE Systems Engineering Handbook: "homogeneous entity that exhibits predefined behavior in the real world and is composed of heterogeneous parts that do not individually exhibit that behavior and an integrated configuration of components and/or subsystems."[33]
- INCOSE: "A system is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and

documents; that is, all things required to produce systems-level results. The results include system level qualities, properties, characteristics, functions, behavior and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected."[34]

The systems engineering process

Depending on their application, tools are used for various stages of the systems engineering process:[18]

Using models

Models play important and diverse roles in systems engineering. A model can be defined in several ways, including:[35]

- An abstraction of reality designed to answer specific questions about the real world
- An imitation, analogue, or representation of a real world process or structure; or
- A conceptual, mathematical, or physical tool to assist a decision maker.

Together, these definitions are broad enough to encompass physical engineering models used in the verification of a system design, as well as schematic models like a functional flow block diagram and mathematical (i.e., quantitative) models used in the trade study process. This section focuses on the last.[35]

The main reason for using mathematical models and diagrams in trade studies is to provide estimates of system effectiveness, performance or technical attributes, and cost from a set of known or estimable quantities. Typically, a collection of separate models is needed to provide all of these outcome variables. The heart of any mathematical model is a set of meaningful quantitative relationships among its inputs and outputs. These relationships can be as simple as adding up constituent quantities to obtain a total, or as complex as a set of differential equations describing the trajectory of a spacecraft in a gravitational field. Ideally, the relationships express causality, not just correlation.[35]

Tools for graphic representations

Initially, when the primary purpose of a systems engineer is to comprehend a complex problem, graphic representations of a system are used to communicate a system's functional and data requirements.[36] Common graphical representations include:

- Functional Flow Block Diagram (FFBD)
- Data Flow Diagram (DFD)
- N2 (N-Squared) Chart
- IDEF0 Diagram
- UML Use case diagram
- UML Sequence diagram
- USL Function Maps and Type Maps.
- Enterprise Architecture frameworks, like TOGAF, MODAF, Zachman Frameworks etc.

A graphical representation relates the various subsystems or parts of a system through functions, data, or interfaces. Any or each of the above methods are used in an industry based on its requirements. For instance, the N2 chart may be used where interfaces between systems is important. Part of the design phase is to create structural and behavioral models of the system.

Once the requirements are understood, it is now the responsibility of a Systems engineer to refine them, and to determine, along with other engineers, the best technology for a job. At this point starting with a trade study, systems engineering encourages the use of weighted choices to determine the best option. A decision matrix, or Pugh method, is one way (QFD is another) to make this choice while considering all criteria that are important. The trade

study in turn informs the design which again affects the graphic representations of the system (without changing the requirements). In an SE process, this stage represents the iterative step that is carried out until a feasible solution is found. A decision matrix is often populated using techniques such as statistical analysis, reliability analysis, system dynamics (feedback control), and optimization methods.

At times a systems engineer must assess the existence of feasible solutions, and rarely will customer inputs arrive at only one. Some customer requirements will produce no feasible solution. Constraints must be traded to find one or more feasible solutions. The customers' wants become the most valuable input to such a trade and cannot be assumed. Those wants/desires may only be discovered by the customer once the customer finds that he has overconstrained the problem. Most commonly, many feasible solutions can be found, and a sufficient set of constraints must be defined to produce an optimal solution. This situation is at times advantageous because one can present an opportunity to improve the design towards one or many ends, such as cost or schedule. Various modeling methods can be used to solve the problem including constraints and a cost function.

Systems Modeling Language (SysML), a modeling language used for systems engineering applications, supports the specification, analysis, design, verification and validation of a broad range of complex systems.[37]

Universal Systems Language (USL) is a systems oriented object modeling language with executable (computer independent) semantics for defining complex systems, including software.[38]

Closely related fields

Many related fields may be considered tightly coupled to systems engineering. These areas have contributed to the development of systems engineering as a distinct entity.

Cognitive systems engineering

Cognitive systems engineering (CSE) is a specific approach to the description and analysis of human-machine systems or sociotechnical systems.[39] The three main themes of CSE are how humans cope with complexity, how work is accomplished by the use of artefacts, and how human-machine systems and socio-technical systems can be described as joint cognitive systems. CSE has since its beginning become a recognised scientific discipline, sometimes also referred to as Cognitive Engineering. The concept of a Joint Cognitive System (JCS) has in particular become widely used as a way of understanding how complex socio-technical systems can be described with varying degrees of resolution. The experience with CSE has been described in two books that summarises the field after more than 20 years of work, namely[40] and [41] .

Configuration Management

Like Systems Engineering, Configuration Management as practiced in the defence and aerospace industry is a broad systems-level practice. The field parallels the taskings of Systems Engineering; where Systems Engineering deals with requirements development, allocation to development items and verification, Configuration Management deals with requirements capture, traceability to the development item, and audit of development item to ensure that it has achieved the desired functionality that Systems Engineering and/or Test and Verification Engineering have proven out through objective testing.

Control engineering

Control engineering and its design and implementation of control systems, used extensively in nearly every industry, is a large sub-field of Systems Engineering. The cruise control on an automobile and the guidance system for a ballistic missile are two examples. Control systems theory is an active field of applied mathematics involving the investigation of solution spaces and the development of new methods for the analysis of the control process.

Industrial engineering

Industrial engineering is a branch of engineering that concerns the development, improvement, implementation and evaluation of integrated systems of people, money, knowledge, information, equipment,

energy, material and process. Industrial engineering draws upon the principles and methods of engineering analysis and synthesis, as well as mathematical, physical and social sciences together with the principles and methods of engineering analysis and design to specify, predict and evaluate the results to be obtained from such systems.

Interface design

Interface design and its specification are concerned with assuring that the pieces of a system connect and inter-operate with other parts of the system and with external systems as necessary. Interface design also includes assuring that system interfaces be able to accept new features, including mechanical, electrical and logical interfaces, including reserved wires, plug-space, command codes and bits in communication protocols. This is known as extensibility. Human-Computer Interaction (HCI) or Human-Machine Interface (HMI) is another aspect of interface design, and is a critical aspect of modern Systems Engineering. Systems engineering principles are applied in the design of network protocols for local-area networks and wide-area networks.

Operations research

Operations research supports systems engineering. The tools of operations research are used in systems analysis, decision making, and trade studies. Several schools teach SE courses within the operations research or industrial engineering department, highlighting the role systems engineering plays in complex projects. operations research, briefly, is concerned with the optimization of a process under multiple constraints.[42]

Reliability engineering

Reliability engineering is the discipline of ensuring a system will meet the customer's expectations for reliability throughout its life; i.e. it will not fail more frequently than expected. Reliability engineering applies to all aspects of the system. It is closely associated with maintainability, availability and logistics engineering. Reliability engineering is always a critical component of safety engineering, as in failure modes and effects analysis (FMEA) and hazard fault tree analysis, and of security engineering. Reliability engineering relies heavily on statistics, probability theory and reliability theory for its tools and processes.

Performance engineering

Performance engineering is the discipline of ensuring a system will meet the customer's expectations for performance throughout its life. Performance is usually defined as the speed with which a certain operation is executed or the capability of executing a number of such operations in a unit of time. Performance may be degraded when an operations queue to be executed is throttled when the capacity is of the system is limited. For example, the performance of a packet-switched network would be characterised by the end-to-end packet transit delay or the number of packets switched within an hour. The design of high-performance systems makes use of analytical or simulation modeling, whereas the delivery of high-performance implementation involves thorough performance testing. Performance engineering relies heavily on statistics, queuing theory and probability theory for its tools and processes.

Program management and project management.

Program management (or programme management) has many similarities with systems engineering, but has broader-based origins than the engineering ones of systems engineering. Project management is also closely related to both program management and systems engineering.

Safety engineering

The techniques of safety engineering may be applied by non-specialist engineers in designing complex systems to minimize the probability of safety-critical failures. The "System Safety Engineering" function helps to identify "safety hazards" in emerging designs, and may assist with techniques to "mitigate" the effects of (potentially) hazardous conditions that cannot be designed out of systems.

Security engineering

Security engineering can be viewed as an interdisciplinary field that integrates the community of practice for control systems design, reliability, safety and systems engineering. It may involve such sub-specialties as authentication of system users, system targets and others: people, objects and processes.

Software engineering

From its beginnings Software engineering has helped shape modern Systems Engineering practice. The techniques used in the handling of complexes of large software-intensive systems has had a major effect on the shaping and reshaping of the tools, methods and processes of SE.

See also

Lists

- List of production topics
- List of systems engineers
- List of types of systems engineering
- List of systems engineering at universities

Topics

- Management cybernetics
- Enterprise systems engineering
- System of systems engineering (SoSE)

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External links

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- Shishko, Robert et al. *NASA Systems Engineering Handbook.* [46] NASA Center for AeroSpace Information, 2005.
- Systems Engineering Handbook [47] NASA/SP-2007-6105 Rev1, December 2007.
- Derek Hitchins, *World Class Systems Engineering* [48], 1997.
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Sociobiology

Sociobiology is a synthesis of scientific disciplines which attempts to explain social behavior in animal species by considering the Darwinian advantages specific behaviors may have. It is often considered a branch of biology and sociology, but also draws from ethology, anthropology, evolution, zoology, archaeology, population genetics and other disciplines. Within the study of human societies, sociobiology is closely related to the fields of human behavioral ecology and evolutionary psychology.

Sociobiology investigates social behaviors, such as mating patterns, territorial fights, pack hunting, and the hive society of social insects. Just as selection pressure led to animals evolving useful ways of interacting with the natural environment, it led to the genetic evolution of advantageous social behavior.

Sociobiology has become one of the greatest scientific controversies of the late 20th and early 21st centuries, especially in the context of explaining human behavior. Applied to non-humans, sociobiology is uncontroversial. Criticism, most notably made by Richard Lewontin and Stephen Jay Gould, centers on sociobiology's contention that genes play an ultimate role in human behavior and that traits such as aggressiveness can be explained by biology rather than a person's social environment. Many sociobiologists, however, cite a complex relationship between nature and nurture. In response to the controversy, anthropologist John Tooby and psychologist Leda Cosmides launched evolutionary psychology as a branch of sociobiology made less controversial by avoiding questions of human biodiversity.

Definition

E.O. Wilson defines sociobiology as: "The extension of population biology and evolutionary theory to social organisation"[1]

Sociobiology is based on the premise that some behaviors (both social and individual) are at least partly inherited and can be affected by natural selection. It begins with the idea that behaviors have evolved over time, similar to the way that physical traits are thought to have evolved. It predicts therefore that animals will act in ways that have proven to be evolutionarily successful over time, which can among other things result in the formation of complex social processes conducive to evolutionary fitness.

The discipline seeks to explain behavior as a product of natural selection. Behavior is therefore seen as an effort to preserve one's genes in the population. Inherent in sociobiological reasoning is the idea that certain genes or gene

combinations that influence particular behavioral traits can be inherited from generation to generation.

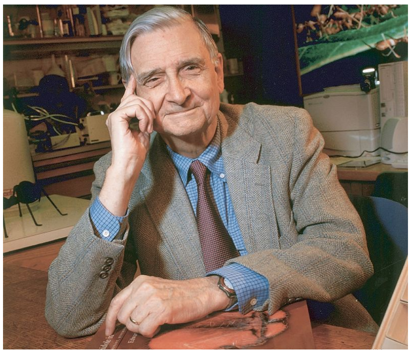
Introductory examples

For example, newly dominant male lions often will kill cubs in the pride that were not sired by them. This behaviour is adaptive in evolutionary terms because killing the cubs eliminates competition for their own offspring and causes the nursing females to come into heat faster, thus allowing more of his genes to enter into the population. Sociobiologists would view this instinctual cub-killing behavior as being inherited through the genes of successfully reproducing male lions, whereas non-killing behaviour may have "died out" as those lions were less successful in reproducing.

Genetic mouse mutants have now been harnessed to illustrate the power that genes exert on behaviour. For example, the transcription factor FEV (aka Pet1) has been shown, through its role in maintaining the serotonergic system in the brain, to be required for normal aggressive and anxiety-like behavior[2] . Thus, when FEV is genetically deleted from the mouse genome, male mice will instantly attack other males, whereas their wild-type counterparts take significantly longer to initiate violent behaviour. In addition, FEV has been shown to be required for correct maternal behaviour in mice, such that their offspring do not survive unless cross-fostered to other wild-type female mice[3]

A genetic basis for instinctive behavioural traits among non-human species, such as in the above example, is commonly accepted among many biologists; however, attempting to use a genetic basis to explain complex behaviours in human societies has remained extremely controversial.

History



E. O. Wilson, a central figure in the history of sociobiology.

According to the OED, John Paul Scott coined the word "sociobiology" at a 1946 conference on genetics and social behaviour, and became widely used after it was popularized by Edward O. Wilson in his 1975 book, *Sociobiology: The New Synthesis*. However, the influence of evolution on behavior has been of interest to biologists and philosophers since soon after the discovery of the evolution itself. Peter Kropotkin's *Mutual Aid: A Factor of Evolution*, written in the early 1890s, is a popular example. Antecedents of modern sociobiological thinking can be traced to the 1960s and the work of such biologists as Robert Trivers and William D. Hamilton.

Nonetheless, it was Wilson's book that pioneered and popularized the attempt to explain the evolutionary mechanics behind social behaviors such as altruism, aggression, and nurturence, primarily in ants (Wilson's own research specialty) but also in other animals. The final chapter of the book is devoted to sociobiological explanations of human behavior, and Wilson later wrote a Pulitzer Prize winning book, *On Human Nature*, that addressed human behavior specifically.

Sociobiological theory

Sociobiologists believe that human behavior, as well as nonhuman animal behavior, can be partly explained as the outcome of natural selection. They contend that in order fully to understand behavior, it must be analyzed in terms of evolutionary considerations.

Natural selection is fundamental to evolutionary theory. Variants of hereditary traits which increase an organism's ability to survive and reproduce will be more greatly represented in subsequent generations, i.e., they will be "selected for". Thus, inherited behavioral mechanisms that allowed an organism a greater chance of surviving and/or reproducing in the past are more likely to survive in present organisms. That inherited adaptive behaviors are present in nonhuman animal species has been multiply demonstrated by biologists, and it has become a foundation of evolutionary biology. However, there is continued resistance by some researchers over the application of evolutionary models to humans, particularly from within the social sciences, where culture has long been assumed to be the predominant driver of behavior.

Sociobiology is based upon two fundamental premises:

- Certain behavioral traits are inherited,
- Inherited behavioral traits have been honed by natural selection. Therefore, these traits were probably "adaptive" in the species` evolutionarily evolved environment.

Sociobiology uses Nikolaas Tinbergen's four categories of questions and explanations of animal behavior. Two categories are at the species level; two, at the individual level. The species-level categories (often called “ultimate explanations”) are

- the function (i.e., adaptation) that a behavior serves and
- the evolutionary process (i.e., phylogeny) that resulted in this functionality.

The individual-level categories (often called “proximate explanations”) are

- the development of the individual (i.e., ontogeny) and
- the proximate mechanism (e.g., brain anatomy and hormones).

Sociobiologists are interested in how behavior can be explained logically as a result of selective pressures in the history of a species. Thus, they are often interested in instinctive, or intuitive behavior, and in explaining the similarities, rather than the differences, between cultures. For example, mothers within many species of mammals – including humans – are very protective of their offspring. Sociobiologists reason that this protective behavior likely evolved over time because it helped those individuals which had the characteristic to survive and reproduce. Over time, individuals who exhibited such protective behaviours would have had more surviving offspring than did those who did not display such behaviours, such that this parental protection would increase in frequency in the population. In this way, the social behavior is believed to have evolved in a fashion similar to other types of nonbehavioral adaptations, such as (for example) fur or the sense of smell.

Individual genetic advantage often fails to explain certain social behaviors as a result of gene-centred selection, and evolution may also act upon groups. The mechanisms responsible for group selection employ paradigms and population statistics borrowed from game theory. E.O. Wilson argued that altruistic individuals must reproduce their own altruistic genetic traits for altruism to survive. When altruists lavish their resources on non-altruists at the expense of their own kind, the altruists tend to die out and the others tend to grow. In other words, altruism is more likely to survive if altruists practice the ethic that "charity begins at home."

Within sociobiology, a social behavior is first explained as a sociobiological hypothesis by finding an evolutionarily stable strategy that matches the observed behavior. Stability of a strategy can be difficult to prove, but usually, a well-formed strategy will predict gene frequencies. The hypothesis can be supported by establishing a correlation between the gene frequencies predicted by the strategy, and those expressed in a population. Measurement of genes and gene-frequencies can be problematic, however, because a simple statistical correlation can be open to charges of circularity (Circularity can occur if the measurement of gene frequency indirectly uses the same measurements that

describe the strategy).

Altruism between social insects and littermates has been explained in such a way. Altruistic behavior in some animals has been correlated to the degree of genome shared between altruistic individuals. A quantitative description of infanticide by male harem-mating animals when the alpha male is displaced as well as rodent female infanticide and fetal resorption are active areas of study. In general, females with more bearing opportunities may value offspring less, and may also arrange bearing opportunities to maximize the food and protection from mates.

An important concept in sociobiology is that temperamental traits within a gene pool and between gene pools exist in an ecological balance. Just as an expansion of a sheep population might encourage the expansion of a wolf population, an expansion of altruistic traits within a gene pool may also encourage the expansion of individuals with dependent traits.

Sociobiology is sometimes associated with arguments over the "genetic" basis of intelligence. While sociobiology is predicated on the observation that genes do affect behavior, it is perfectly consistent to be a sociobiologist while arguing that measured IQ variations between individuals reflect mainly cultural or economic rather than genetic factors. However, many critics point out that the usefulness of sociobiology as an explanatory tool breaks down once a trait is so variable as to no longer be exposed to selective pressures. In order to explain aspects of human intelligence as the outcome of selective pressures, it must be demonstrated that those aspects are inherited, or genetic, but this does not necessarily imply differences among individuals: a common genetic inheritance could be shared by *all* humans, just as the genes responsible for number of limbs are shared by all individuals. An even more sensitive subject is race and intelligence.

Researchers performing twin studies have argued that differences between people on behavioral traits such as creativity, extroversion and aggressiveness are between 45% to 75% due to genetic differences, and intelligence is said by some to be about 80% genetic after one matures (discussed at Intelligence quotient#Genetics vs environment). However, critics (such as the evolutionary geneticist R. C Lewontin) have highlighted serious flaws in twin studies, such as the inability of researchers to separate environmental, genetic, and dialectic effects on twins.[4]

Criminality is actively under study, but extremely controversial. There are arguments that in some environments criminal behavior might be adaptive.[5]

Criticism

Many critics draw an intellectual link between sociobiology and biological determinism, the belief that most human differences can be traced to specific genes rather than differences in culture or social environments. Critics also draw parallels between biological determinism as an underlying philosophy to the social Darwinian and eugenics movements of the early 20th century, and controversies in the history of intelligence testing. Steven Pinker argues that critics have been overly swayed by politics and a "fear" of biological determinism.[6] However, all these critics have claimed that sociobiology fails on scientific grounds, independent of their political critiques. In particular, Lewontin, Rose & Kamin drew a detailed distinction between the politics and history of an idea and its scientific validity,[4] as has Stephen Jay Gould.[7]

Wilson and his supporters counter the intellectual link by denying that Wilson had a political agenda, still less a right-wing one. They pointed out that Wilson had personally adopted a number of liberal political stances and had attracted progressive sympathy for his outspoken environmentalism. They argued that as scientists they had a duty to uncover the truth whether that was politically correct or not. They argued that sociobiology does not necessarily lead to any particular political ideology as many critics implied. Many subsequent sociobiologists, including Robert Wright, Anne Campbell, Frans de Waal and Sarah Blaffer Hrdy, have used sociobiology to argue quite separate points. Noam Chomsky came to the defense of sociobiology's methodology, noting that it was the same methodology he used in his work on linguistics. However, he roundly criticized the sociobiologists' actual conclusions about humans as lacking substance. He also noted that the anarchist Peter Kropotkin had made similar arguments in his book *Mutual Aid: A Factor of Evolution*, although focusing more on altruism than aggression, suggesting that

anarchist societies were feasible because of an innate human tendency to cooperate.[8]

Wilson's claims that he had never meant to imply what *ought* to be, only what *is* the case are supported by his writings, which are descriptive, not prescriptive. However, many critics have pointed out that the language of sociobiology often slips from "is" to "ought",[4] leading sociobiologists to make arguments against social reform on the basis that socially progressive societies are at odds with our innermost nature. For example, some groups have supported positions of ethnic nepotism.[9] Views such as this, however, are often criticized as examples of the naturalistic fallacy, when reasoning jumps from descriptions about what *is* to prescriptions about what *ought* to be. (A common example is the justification of militarism if scientific evidence showed warfare was part of human nature.) It has also been argued that opposition to stances considered anti-social, such as ethnic nepotism, are based on moral assumptions, not bioscientific assumptions, meaning that it is not vulnerable to being disproved by bioscientific advances.[6] :145 The history of this debate, and others related to it, are covered in detail by Cronin (1992), Segerstråle (2000) and Alcock (2001). Adaptationists such as Steven Pinker have also suggested that the debate has a strong ad hominem component.

See also

Concepts

- Biocultural anthropology
- Biosocial theory
- Cultural selection theory
- Dual inheritance theory
- Ethics and evolutionary psychology
- Evolutionary psychology
- Evolutionary developmental psychology
- Human behavioral ecology
- Iterated prisoner's dilemma
- Kin selection
- Prisoner's dilemma
- Social evolution
- Sociophysiology
- Evolutionary ethics

Well-known sociobiologists

- Richard Dawkins
- Edward O. Wilson
- W. D. Hamilton
- Robert Trivers
- George C. Williams
- Sarah Blaffer Hrdy
- Richard Machalek
- Steven Pinker
- Francois Nielsen

Books

- *Sociobiology: The New Synthesis* by E. O. Wilson, 1975
- *The Blank Slate: The Modern Denial of Human Nature* by Steven Pinker
- *The Selfish Gene* by Richard Dawkins
- *Biology, Ideology and Human Nature: Not In Our Genes* by Richard Lewontin, Steven Rose & Leon Kamin

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External links

- Sociobiology [10] (Stanford Encyclopedia of Philosophy) - Harmon Holcomb [11] & Jason Byron [12]
- The Sociobiology of Sociopathy, Mealey, 1995 [13]
- Speak, Darwinists! [14] Interviews with leading sociobiologists.
- Race and Creation [15] - Richard Dawkins
- Genetic Similarity and Ethnic Nationalism [16] - An Attempted Sociobiological Explanation of the scientific basis for Political Group Formation.
- A brief history on sociobiology [17]

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[12] http://www.pitt.edu/~jmb165

[13] http://www.bbsonline.org/Preprints/OldArchive/bbs.mealey.html

[14] http://www.froes.dds.nl

[15] http://www.prospect-magazine.co.uk/article_details.php?id=6467
[16] http://www.psychology.uwo.ca/faculty/rushtonpdfs/N&N%202005-1.pdf
[17] http://www.nytimes.com/2008/07/15/science/15wils.html?pagewanted=1

Theoretical biology

Mathematical and theoretical biology is an interdisciplinary academic research field with a range of applications in biology, medicine and biotechnology.[1] The field may be referred to as **mathematical biology** or **biomathematics** to stress the mathematical side, or as **theoretical biology** to stress the biological side.[2] It includes at least four major subfields: *biological mathematical modeling*, *relational biology/complex systems biology (CSB)*, *bioinformatics* and *computational biomodeling/biocomputing*.

Mathematical biology aims at the mathematical representation, treatment and modeling of biological processes, using a variety of applied mathematical techniques and tools. It has both theoretical and practical applications in biological, biomedical and biotechnology research. For example, in cell biology, protein interactions are often represented as "cartoon" models, which, although easy to visualize, do not accurately describe the systems studied. In order to do this, precise mathematical models are required. By describing the systems in a quantitative manner, their behavior can be better simulated, and hence properties can be predicted that might not be evident to the experimenter.

Importance

Applying mathematics to biology has a long history, but only recently has there been an explosion of interest in the field. Some reasons for this include:

- the explosion of data-rich information sets, due to the genomics revolution, which are difficult to understand without the use of analytical tools,
- recent development of mathematical tools such as chaos theory to help understand complex, nonlinear mechanisms in biology,
- an increase in computing power which enables calculations and simulations to be performed that were not previously possible, and
- an increasing interest in in silico experimentation due to ethical considerations, risk, unreliability and other complications involved in human and animal research.

Areas of research

Several areas of specialized research in mathematical and theoretical biology[3] [4] [5] [6] [7] as well as external links to related projects in various universities are concisely presented in the following subsections, including also a large number of appropriate validating references from a list of several thousands of published authors contributing to this field. Many of the included examples are characterised by highly complex, nonlinear, and supercomplex mechanisms, as it is being increasingly recognised that the result of such interactions may only be understood through a combination of mathematical, logical, physical/chemical, molecular and computational models. Due to the wide diversity of specific knowledge involved, biomathematical research is often done in collaboration between mathematicians, biomathematicians, theoretical biologists, physicists, biophysicists, biochemists, bioengineers, engineers, biologists, physiologists, research physicians, biomedical researchers, oncologists, molecular biologists, geneticists, embryologists, zoologists, chemists, etc.

Computer models and automata theory

A monograph on this topic summarizes an extensive amount of published research in this area up to 1987,[8] including subsections in the following areas: computer modeling in biology and medicine, arterial system models, neuron models, biochemical and oscillation networks, quantum automata [9], quantum computers in molecular biology and genetics, cancer modelling, neural nets, genetic networks, abstract relational biology, metabolic-replication systems, category theory[9] applications in biology and medicine,[10] automata theory, cellular automata, tessallation models[11] [12] and complete self-reproduction [14], chaotic systems in organisms, relational biology and organismic theories.[13] [14] This published report also includes 390 references to peer-reviewed articles by a large number of authors.[3] [15] [16]

Modeling cell and molecular biology

This area has received a boost due to the growing importance of molecular biology.[6]

- Mechanics of biological tissues[17]
- Theoretical enzymology and enzyme kinetics
- Cancer modelling and simulation[18] [19]
- Modelling the movement of interacting cell populations[20]
- Mathematical modelling of scar tissue formation[21]
- Mathematical modelling of intracellular dynamics[22]
- Mathematical modelling of the cell cycle[23]

Modelling physiological systems

- Modelling of arterial disease [24]
- Multi-scale modelling of the heart [25]

Molecular set theory

Molecular set theory was introduced by Anthony Bartholomay, and its applications were developed in mathematical biology and especially in Mathematical Medicine.[26] Molecular set theory (MST) is a mathematical formulation of the wide-sense chemical kinetics of biomolecular reactions in terms of sets of molecules and their chemical transformations represented by set-theoretical mappings between molecular sets. In a more general sense, MST is the theory of molecular categories defined as categories of molecular sets and their chemical transformations represented as set-theoretical mappings of molecular sets. The theory has also contributed to biostatistics and the formulation of clinical biochemistry problems in mathematical formulations of pathological, biochemical changes of interest to Physiology, Clinical Biochemistry and Medicine.[26] [27]

Population dynamics

Population dynamics has traditionally been the dominant field of mathematical biology. Work in this area dates back to the 19th century. The Lotka–Volterra predator-prey equations are a famous example. In the past 30 years, population dynamics has been complemented by evolutionary game theory, developed first by John Maynard Smith. Under these dynamics, evolutionary biology concepts may take a deterministic mathematical form. Population dynamics overlap with another active area of research in mathematical biology: mathematical epidemiology, the study of infectious disease affecting populations. Various models of the spread of infections have been proposed and analyzed, and provide important results that may be applied to health policy decisions.

Mathematical methods

A model of a biological system is converted into a system of equations, although the word 'model' is often used synonymously with the system of corresponding equations. The solution of the equations, by either analytical or numerical means, describes how the biological system behaves either over time or at equilibrium. There are many different types of equations and the type of behavior that can occur is dependent on both the model and the equations used. The model often makes assumptions about the system. The equations may also make assumptions about the nature of what may occur.

Mathematical biophysics

The earlier stages of mathematical biology were dominated by mathematical biophysics, described as the application of mathematics in biophysics, often involving specific physical/mathematical models of biosystems and their components or compartments.

The following is a list of mathematical descriptions and their assumptions.

Deterministic processes (dynamical systems)

A fixed mapping between an initial state and a final state. Starting from an initial condition and moving forward in time, a deterministic process will always generate the same trajectory and no two trajectories cross in state space.

- Difference equations/Maps – discrete time, continuous state space.
- Ordinary differential equations – continuous time, continuous state space, no spatial derivatives. *See also:* Numerical ordinary differential equations.
- Partial differential equations – continuous time, continuous state space, spatial derivatives. *See also:* Numerical partial differential equations.

Stochastic processes (random dynamical systems)

A random mapping between an initial state and a final state, making the state of the system a random variable with a corresponding probability distribution.

- Non-Markovian processes – generalized master equation – continuous time with memory of past events, discrete state space, waiting times of events (or transitions between states) discretely occur and have a generalized probability distribution.
- Jump Markov process – master equation – continuous time with no memory of past events, discrete state space, waiting times between events discretely occur and are exponentially distributed. *See also:* Monte Carlo method for numerical simulation methods, specifically continuous-time Monte Carlo which is also called kinetic Monte Carlo or the stochastic simulation algorithm.
- Continuous Markov process – stochastic differential equations or a Fokker-Planck equation – continuous time, continuous state space, events occur continuously according to a random Wiener process.

Spatial modelling

One classic work in this area is Alan Turing's paper on morphogenesis entitled *The Chemical Basis of Morphogenesis*, published in 1952 in the Philosophical Transactions of the Royal Society.

- Travelling waves in a wound-healing assay[28]
- Swarming behaviour[29]
- A mechanochemical theory of morphogenesis[30]
- Biological pattern formation[31]
- Spatial distribution modeling using plot samples[32]

Phylogenetics

Phylogenetics is an area that deals with the reconstruction and analysis of phylogenetic (evolutionary) trees and networks based on inherited characteristics[33]

Model example: the cell cycle

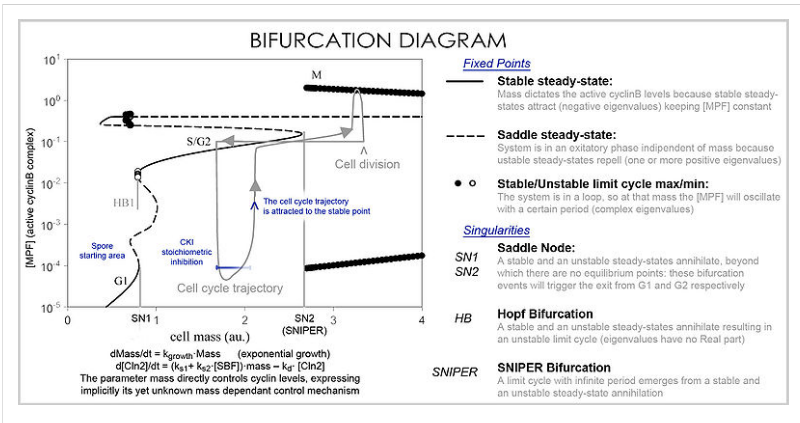
The eukaryotic cell cycle is very complex and is one of the most studied topics, since its misregulation leads to cancers. It is possibly a good example of a mathematical model as it deals with simple calculus but gives valid results. Two research groups [34] [35] have produced several models of the cell cycle simulating several organisms. They have recently produced a generic eukaryotic cell cycle model which can represent a particular eukaryote depending on the values of the parameters, demonstrating that the idiosyncrasies of the individual cell cycles are due to different protein concentrations and affinities, while the underlying mechanisms are conserved (Csikasz-Nagy et al., 2006).

By means of a system of ordinary differential equations these models show the change in time (dynamical system) of the protein inside a single typical cell; this type of model is called a deterministic process (whereas a model describing a statistical distribution of protein concentrations in a population of cells is called a stochastic process).

To obtain these equations an iterative series of steps must be done: first the several models and observations are combined to form a consensus diagram and the appropriate kinetic laws are chosen to write the differential equations, such as rate kinetics for stoichiometric reactions, Michaelis-Menten kinetics for enzyme substrate reactions and Goldbeter–Koshland kinetics for ultrasensitive transcription factors, afterwards the parameters of the equations (rate constants, enzyme efficiency coefficients and Michealis constants) must be fitted to match observations; when they cannot be fitted the kinetic equation is revised and when that is not possible the wiring diagram is modified. The parameters are fitted and validated using observations of both wild type and mutants, such as protein half-life and cell size.

In order to fit the parameters the differential equations need to be studied. This can be done either by simulation or by analysis.

In a simulation, given a starting vector (list of the values of the variables), the progression of the system is calculated by solving the equations at each time-frame in small increments.



In analysis, the proprieties of the equations are used to investigate the behavior of the system depending of the values of the parameters and variables. A system of differential equations can be represented as a vector field, where each vector described the change (in concentration of two or more protein) determining where and how fast the trajectory (simulation) is heading. Vector fields can have several special points: a stable point, called a sink, that attracts in all directions (forcing the concentrations to be at a certain value), an unstable point, either a source or a saddle point which repels (forcing the concentrations to change away from a certain value), and a limit cycle, a closed trajectory towards which several trajectories spiral towards (making the concentrations oscillate).

A better representation which can handle the large number of variables and parameters is called a bifurcation diagram(Bifurcation theory): the presence of these special steady-state points at certain values of a parameter (e.g. mass) is represented by a point and once the parameter passes a certain value, a qualitative change occurs, called a

bifurcation, in which the nature of the space changes, with profound consequences for the protein concentrations: the cell cycle has phases (partially corresponding to G1 and G2) in which mass, via a stable point, controls cyclin levels, and phases (S and M phases) in which the concentrations change independently, but once the phase has changed at a bifurcation event (Cell cycle checkpoint), the system cannot go back to the previous levels since at the current mass the vector field is profoundly different and the mass cannot be reversed back through the bifurcation event, making a checkpoint irreversible. In particular the S and M checkpoints are regulated by means of special bifurcations called a Hopf bifurcation and an infinite period bifurcation.

See also

- Abstract relational biology [38][36] [37]
- Artificial life
- Biocybernetics
- Bioinformatics
- Biologically inspired computing
- Biosemiotics
- Biostatistics
- Cellular automata[3]
- Coalescent theory
- Complex systems biology[38] [3] [39]
- Computational biology
- Digital morphogenesis
- Dynamical systems in biology[3] [39] [40] [41] [42] [43]
- Epidemiology
- Evolution theories and Population Genetics
  - Population genetics models
  - Molecular evolution theories
- Ewens's sampling formula
- Excitable medium
- Journal of Theoretical Biology
- Mathematical models
  - Molecular modelling
  - Molecular modelling on GPU
  - Software for molecular modeling
  - Metabolic-replication systems[44]
  - Models of Growth and Form
  - Neighbour-sensing model
- Morphometrics
- Organismic systems (OS) [48][45]
- Organismic supercategories [48][39] [46]
- Population dynamics of fisheries
- Protein folding, also blue Gene and folding@home
- Quantum computers
- Quantum genetics
- Relational biology[47]
- Self-reproduction[48] (also called self-replication in a more general context).
- Computational gene models

- Systems biology[49]
- Theoretical biology[50]
- Theoretical ecology
- Topological models of morphogenesis
  - DNA topology
  - DNA sequencing theory

  For use of basic arithmetics in biology, see relevant topic, such as Serial dilution.

- Biographies
  - Charles Darwin
  - D'Arcy Thompson
  - Joseph Fourier
  - Charles S. Peskin
  - Nicolas Rashevsky [55]
  - Robert Rosen
  - Rosalind Franklin
  - Francis Crick
  - René Thom
  - Vito Volterra

Societies and Institutes

- Division of Mathematical Biology at NIMR
- Society for Mathematical Biology
- European Society for Mathematical and Theoretical Biology

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Further reading

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External links

- The Society for Mathematical Biology [60]
- Theoretical and mathematical biology website [61]
- Complexity Discussion Group [62]
- UCLA Biocybernetics Laboratory [63]
- TUCS Computational Biomodelling Laboratory [64]
- Nagoya University Division of Biomodeling [65]
- Technische Universiteit Biomodeling and Informatics [66]
- BioCybernetics Wiki, a vertical wiki on biomedical cybernetics and systems biology [67]
- Bulletin of Mathematical Biology [68]
- European Society for Mathematical and Theoretical Biology [69]
- Journal of Mathematical Biology [70]
- Biomathematics Research Centre at University of Canterbury [71]
- Centre for Mathematical Biology at Oxford University [72]
- Mathematical Biology at the National Institute for Medical Research [73]
- Institute for Medical BioMathematics [74]
- *Mathematical Biology Systems of Differential Equations* [75] from EqWorld: The World of Mathematical Equations
- Systems Biology Workbench - a set of tools for modelling biochemical networks [76]
- The Collection of Biostatistics Research Archive [77]
- Statistical Applications in Genetics and Molecular Biology [78]
- The International Journal of Biostatistics [79]
- Theoretical Modeling of Cellular Physiology at Ecole Normale Superieure, Paris [80]

Lists of references

- A general list of Theoretical biology/Mathematical biology references, including an updated list of actively contributing authors [61].
- A list of references for applications of category theory in relational biology [81].
- An updated list of publications of theoretical biologist Robert Rosen [82]
- Theory of Biological Anthropology (Documents No. 9 and 10 in English) [83]
- Drawing the Line Between Theoretical and Basic Biology (a forum article by Isidro T. Savillo) [84]

Related journals

- Acta Biotheoretica [85]
- Bioinformatics [86]
- Biological Theory [87]
- BioSystems [88]
- Bulletin of Mathematical Biology [68]
- Ecological Modelling [89]
- Journal of Mathematical Biology [70]
- Journal of Theoretical Biology [90]
- Journal of the Royal Society Interface [91]
- Mathematical Biosciences [92]
- Medical Hypotheses [93]
- Rivista di Biologia-Biology Forum [94]
- Theoretical and Applied Genetics [95]
- Theoretical Biology and Medical Modelling [96]

- Theoretical Population Biology [97]
- Theory in Biosciences [98] (formerly: Biologisches Zentralblatt)

Related societies

- ESMTB: European Society for Mathematical and Theoretical Biology [69]
- The Israeli Society for Theoretical and Mathematical Biology [99]
- Société Francophone de Biologie Théorique [100]
- International Society for Biosemiotic Studies [101]

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Theoretical genetics

Population genetics is the study of allele frequency distribution and change under the influence of the four main evolutionary processes: natural selection, genetic drift, mutation and gene flow. It also takes into account the factors of population subdivision and population structure. It attempts to explain such phenomena as adaptation and speciation.

Population genetics was a vital ingredient in the emergence of the modern evolutionary synthesis. Its primary founders were Sewall Wright, J. B. S. Haldane and R. A. Fisher, who also laid the foundations for the related discipline of quantitative genetics.

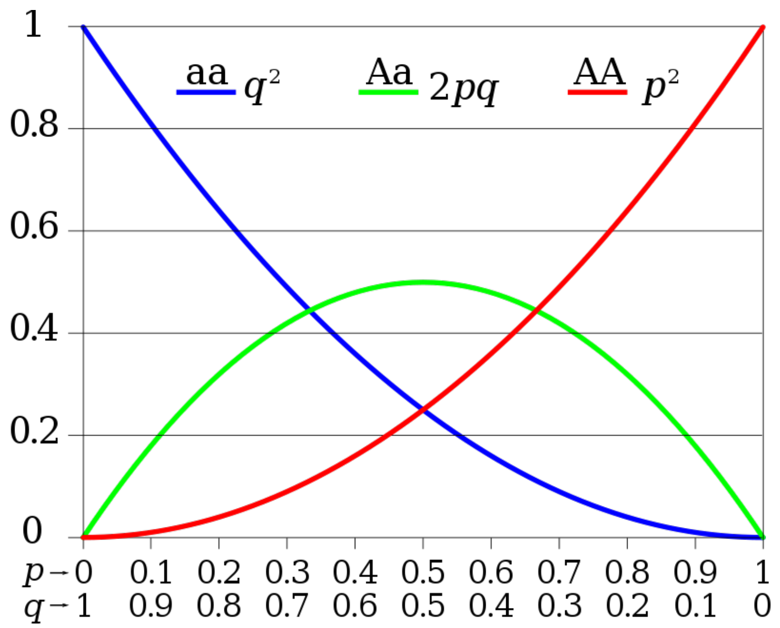
Fundamentals

Population genetics concerns the genetic constitution of populations and how this constitution changes with time. A population is a set of organisms in which any pair of members can breed together. This implies that all members belong to the same species and live near each other.[1]

For example, all of the moths of the same species living in an isolated forest are a population. A gene in this population may have several alternate forms, which account for variations between the phenotypes of the organisms. An example might be a gene for coloration in moths that has two alleles: black and white. A gene pool is the complete set of alleles for a gene in a single population; the allele frequency for an allele is the fraction of the genes in the pool that is composed of that allele (for example, what fraction of moth coloration genes are the black allele). Evolution occurs when there are changes in the frequencies of alleles within a population of interbreeding organisms; for example, the allele for black color in a population of moths becoming more common.

To understand the mechanisms that cause a population to evolve, it is useful to consider what conditions are required for a population not to evolve. The *Hardy-Weinberg principle* states that the frequencies of alleles (variations in a gene) in a sufficiently large population will remain constant if the only forces acting on that population are the random reshuffling of alleles during the formation of the sperm or egg, and the random combination of the alleles in these sex cells during fertilization.[2] Such a population is said to be in *Hardy-Weinberg equilibrium* as it is not evolving.[3]

Hardy–Weinberg principle



Hardy–Weinberg principle for two alleles: the horizontal axis shows the two allele frequencies p and q and the vertical axis shows the genotype frequencies. Each graph shows one of the three possible genotypes.

The *Hardy–Weinberg principle* states that both allele and genotype frequencies in a population remain constant—that is, they are in equilibrium—from generation to generation unless specific disturbing influences are introduced. Outside the lab, one or more of these "disturbing influences" are always in effect. Hardy Weinberg equilibrium is impossible in nature. Genetic equilibrium is an ideal state that provides a baseline to measure genetic change against.

Allele frequencies in a population remain static across generations, provided the following conditions are at hand: random mating, no mutation (the alleles don't change), no migration or emigration (no exchange of alleles between populations), infinitely large population size, and no selective pressure for or against any traits.

In the simplest case of a single locus with two alleles: the dominant allele is denoted **A** and the recessive **a** and their frequencies are denoted by p and q; freq(**A**) = p; freq(**a**) = q; $p + q = 1$. If the population is in equilibrium, then we will have freq(**AA**) = p^2 for the **AA** homozygotes in the population, freq(**aa**) = q^2 for the **aa** homozygotes, and freq(**Aa**) = $2pq$ for the heterozygotes.

Based on these equations, useful but difficult-to-measure facts about a population can be determined. For example, a patient's child is a carrier of a recessive mutation that causes cystic fibrosis in homozygous recessive children. The parent wants to know the probability of her grandchildren inheriting the disease. In order to answer this question, the genetic counselor must know the chance that the child will reproduce with a carrier of the recessive mutation. This fact may not be known, but disease frequency is known. We know that the disease is caused by the homozygous recessive genotype; we can use the Hardy–Weinberg principle to work backward from disease occurrence to the frequency of heterozygous recessive individuals.

Scope and theoretical considerations

The mathematics of population genetics were originally developed as part of the modern evolutionary synthesis. According to Beatty (1986), it defines the core of the modern synthesis.

According to Lewontin (1974), the theoretical task for population genetics is a process in two spaces: a "genotypic space" and a "phenotypic space". The challenge of a *complete* theory of population genetics is to provide a set of laws that predictably map a population of genotypes (G_1) to a phenotype space (P_1), where selection takes place, and another set of laws that map the resulting population (P_2) back to genotype space (G_2) where Mendelian genetics can predict the next generation of genotypes, thus completing the cycle. Even leaving aside for the moment the non-Mendelian aspects of molecular genetics, this is clearly a gargantuan task. Visualizing this transformation schematically:

$$G_1 \xrightarrow{T_1} P_1 \xrightarrow{T_2} P_2 \xrightarrow{T_3} G_2 \xrightarrow{T_4} G_1' \rightarrow \cdots$$

(adapted from Lewontin 1974, p. 12). XD

T_1 represents the genetic and epigenetic laws, the aspects of functional biology, or development, that transform a genotype into phenotype. We will refer to this as the "genotype-phenotype map". T_2 is the transformation due to natural selection, T_3 are epigenetic relations that predict genotypes based on the selected phenotypes and finally T_4 the rules of Mendelian genetics.

In practice, there are two bodies of evolutionary theory that exist in parallel, traditional population genetics operating in the genotype space and the biometric theory used in plant and animal breeding, operating in phenotype space. The missing part is the mapping between the genotype and phenotype space. This leads to a "sleight of hand" (as Lewontin terms it) whereby variables in the equations of one domain, are considered parameters or *constants*, where, in a full-treatment they would be transformed themselves by the evolutionary process and are in reality *functions* of the state variables in the other domain. The "sleight of hand" is assuming that we know this mapping. Proceeding as if we do understand it is enough to analyze many cases of interest. For example, if the phenotype is almost one-to-one with genotype (sickle-cell disease) or the time-scale is sufficiently short, the "constants" can be treated as such; however, there are many situations where it is inaccurate.

The four processes

Natural selection

Natural selection is the process by which heritable traits that make it more likely for an organism to survive and successfully reproduce become more common in a population over successive generations.

The natural genetic variation within a population of organisms means that some individuals will survive more successfully than others in their current environment. Factors which affect reproductive success are also important, an issue which Charles Darwin developed in his ideas on sexual selection.

Natural selection acts on the phenotype, or the observable characteristics of an organism, but the genetic (heritable) basis of any phenotype which gives a reproductive advantage will become more common in a population (see allele frequency). Over time, this process can result in adaptations that specialize organisms for particular ecological niches and may eventually result in the emergence of new species.

Natural selection is one of the cornerstones of modern biology. The term was introduced by Darwin in his groundbreaking 1859 book *On the Origin of Species*,[4] in which natural selection was described by analogy to artificial selection, a process by which animals and plants with traits considered desirable by human breeders are systematically favored for reproduction. The concept of natural selection was originally developed in the absence of a valid theory of heredity; at the time of Darwin's writing, nothing was known of modern genetics. The union of traditional Darwinian evolution with subsequent discoveries in classical and molecular genetics is termed the *modern evolutionary synthesis*. Natural selection remains the primary explanation for adaptive evolution.

Genetic drift

Genetic drift is the change in the relative frequency in which a gene variant (allele) occurs in a population due to random sampling and chance. That is, the alleles in the offspring in the population are a random sample of those in the parents. And chance has a role in determining whether a given individual survives and reproduces. A population's allele frequency is the fraction or percentage of its gene copies compared to the total number of gene alleles that share a particular form.[5]

Genetic drift is an important evolutionary process which leads to changes in allele frequencies over time. It may cause gene variants to disappear completely, and thereby reduce genetic variability. In contrast to natural selection, which makes gene variants more common or less common depending on their reproductive success,[6] the changes due to genetic drift are not driven by environmental or adaptive pressures, and may be beneficial, neutral, or

detrimental to reproductive success.

The effect of genetic drift is larger in small populations, and smaller in large populations. Vigorous debates wage among scientists over the relative importance of genetic drift compared with natural selection. Ronald Fisher held the view that genetic drift plays at the most a minor role in evolution, and this remained the dominant view for several decades. In 1968 Motoo Kimura rekindled the debate with his neutral theory of molecular evolution which claims that most of the changes in the genetic material are caused by genetic drift.[7]

Mutation

Mutations are changes in the DNA sequence of a cell's genome and are caused by radiation, viruses, transposons and mutagenic chemicals, as well as errors that occur during meiosis or DNA replication.[8] [9] [10] Errors are introduced particularly often in the process of DNA replication, in the polymerization of the second strand. These errors can also be induced by the organism itself, by cellular processes such as hypermutation.

Mutations can have an impact on the phenotype of an organism, especially if they occur within the protein coding sequence of a gene. Error rates are usually very low (1 error in every 10 million–100 million bases) due to the "proofreading" ability of DNA polymerases.[11] [12] Without proofreading, error rates are a thousand-fold higher. Chemical damage to DNA occurs naturally as well, and cells use DNA repair mechanisms to repair mismatches and breaks in DNA. Nevertheless, the repair sometimes fails to return the DNA to its original sequence.

In organisms that use chromosomal crossover to exchange DNA and recombine genes, errors in alignment during meiosis can also cause mutations.[13] Errors in crossover are especially likely when similar sequences cause partner chromosomes to adopt a mistaken alignment; this makes some regions in genomes more prone to mutating in this way. These errors create large structural changes in DNA sequence—duplications, inversions or deletions of entire regions, or the accidental exchanging of whole parts between different chromosomes (called translocation).

Mutation can result in several different types of change in DNA sequences; these can either have no effect, alter the product of a gene, or prevent the gene from functioning. Studies in the fly *Drosophila melanogaster* suggest that if a mutation changes a protein produced by a gene, this will probably be harmful, with about 70 percent of these mutations having damaging effects, and the remainder being either neutral or weakly beneficial.[14] Due to the damaging effects that mutations can have on cells, organisms have evolved mechanisms such as DNA repair to remove mutations.[8] Therefore, the optimal mutation rate for a species is a trade-off between costs of a high mutation rate, such as deleterious mutations, and the metabolic costs of maintaining systems to reduce the mutation rate, such as DNA repair enzymes.[15] Viruses that use RNA as their genetic material have rapid mutation rates,[16] which can be an advantage since these viruses will evolve constantly and rapidly, and thus evade the defensive responses of e.g. the human immune system.[17]

Mutations can involve large sections of DNA becoming duplicated, usually through genetic recombination.[18] These duplications are a major source of raw material for evolving new genes, with tens to hundreds of genes duplicated in animal genomes every million years.[19] Most genes belong to larger families of genes of shared ancestry.[20] Novel genes are produced by several methods, commonly through the duplication and mutation of an ancestral gene, or by recombining parts of different genes to form new combinations with new functions.[21] [22]

Here, domains act as modules, each with a particular and independent function, that can be mixed together to produce genes encoding new proteins with novel properties.[23] For example, the human eye uses four genes to make structures that sense light: three for color vision and one for night vision; all four arose from a single ancestral gene.[24] Another advantage of duplicating a gene (or even an entire genome) is that this increases redundancy; this allows one gene in the pair to acquire a new function while the other copy performs the original function.[25] [26] Other types of mutation occasionally create new genes from previously noncoding DNA.[27] [28]

Gene flow

Gene flow is the exchange of genes between populations, which are usually of the same species.[29] Examples of gene flow within a species include the migration and then breeding of organisms, or the exchange of pollen. Gene transfer between species includes the formation of hybrid organisms and horizontal gene transfer.

Migration into or out of a population can change allele frequencies, as well as introducing genetic variation into a population. Immigration may add new genetic material to the established gene pool of a population. Conversely, emigration may remove genetic material. As barriers to reproduction between two diverging populations are required for the populations to become new species, gene flow may slow this process by spreading genetic differences between the populations. Gene flow is hindered by mountain ranges, oceans and deserts or even man-made structures such as the Great Wall of China, which has hindered the flow of plant genes.[30]

Depending on how far two species have diverged since their most recent common ancestor, it may still be possible for them to produce offspring, as with horses and donkeys mating to produce mules.[31] Such hybrids are generally infertile, due to the two different sets of chromosomes being unable to pair up during meiosis. In this case, closely related species may regularly interbreed, but hybrids will be selected against and the species will remain distinct. However, viable hybrids are occasionally formed and these new species can either have properties intermediate between their parent species, or possess a totally new phenotype.[32] The importance of hybridization in creating new species of animals is unclear, although cases have been seen in many types of animals,[33] with the gray tree frog being a particularly well-studied example.[34]

Hybridization is, however, an important means of speciation in plants, since polyploidy (having more than two copies of each chromosome) is tolerated in plants more readily than in animals.[35] [36] Polyploidy is important in hybrids as it allows reproduction, with the two different sets of chromosomes each being able to pair with an identical partner during meiosis.[37] Polyploids also have more genetic diversity, which allows them to avoid inbreeding depression in small populations.[38]

Horizontal gene transfer is the transfer of genetic material from one organism to another organism that is not its offspring; this is most common among bacteria.[39] In medicine, this contributes to the spread of antibiotic resistance, as when one bacteria acquires resistance genes it can rapidly transfer them to other species.[40] Horizontal transfer of genes from bacteria to eukaryotes such as the yeast *Saccharomyces cerevisiae* and the adzuki bean beetle *Callosobruchus chinensis* may also have occurred.[41] [42] An example of larger-scale transfers are the eukaryotic bdelloid rotifers, which appear to have received a range of genes from bacteria, fungi, and plants.[43] Viruses can also carry DNA between organisms, allowing transfer of genes even across biological domains.[44] Large-scale gene transfer has also occurred between the ancestors of eukaryotic cells and prokaryotes, during the acquisition of chloroplasts and mitochondria.[45]

Gene flow is the transfer of alleles from one population to another.

Migration into or out of a population may be responsible for a marked change in allele frequencies. Immigration may also result in the addition of new genetic variants to the established gene pool of a particular species or population.

There are a number of factors that affect the rate of gene flow between different populations. One of the most significant factors is mobility, as greater mobility of an individual tends to give it greater migratory potential. Animals tend to be more mobile than plants, although pollen and seeds may be carried great distances by animals or wind.

Maintained gene flow between two populations can also lead to a combination of the two gene pools, reducing the genetic variation between the two groups. It is for this reason that gene flow strongly acts against speciation, by recombining the gene pools of the groups, and thus, repairing the developing differences in genetic variation that would have led to full speciation and creation of daughter species.

For example, if a species of grass grows on both sides of a highway, pollen is likely to be transported from one side to the other and vice versa. If this pollen is able to fertilise the plant where it ends up and produce viable offspring,

then the alleles in the pollen have effectively been able to move from the population on one side of the highway to the other.

Genetic structure

Because of physical barriers to migration, along with limited vagility, and natal philopatry, natural populations are rarely panmictic (Buston *et al.*, 2007). There is usually a geographic range within which individuals are more closely related to one another than those randomly selected from the general population. This is described as the extent to which a population is genetically structured (Repaci *et al.*, 2007).

Microbial population genetics

Microbial population genetics is a rapidly advancing field of investigation with relevance to many other theoretical and applied areas of scientific investigations. The population genetics of microorganisms lays the foundations for tracking the origin and evolution of antibiotic resistance and deadly infectious pathogens. Population genetics of microorganisms is also an essential factor for devising strategies for the conservation and better utilization of beneficial microbes (Xu, 2010).

History

Biston betularia f. typica is the white-bodied form of the peppered moth.

Biston betularia f. carbonaria is the black-bodied form of the peppered moth.

Population genetics

The Mendelian and biometrician models were eventually reconciled, when *population genetics* was developed. A key step was the work of the British biologist and statistician R.A. Fisher. In a series of papers starting in 1918 and culminating in his 1930 book *The Genetical Theory of Natural Selection*, Fisher showed that the continuous variation measured by the biometricians could be produced by the combined action of many discrete genes, and that natural selection could change gene frequencies in a population, resulting in evolution. In a series of papers beginning in 1924, another British geneticist, J.B.S. Haldane, applied statistical analysis to real-world examples of natural selection, such as the evolution of industrial melanism in peppered moths, and showed that natural selection worked at an even faster rate than Fisher assumed.[46] [47]

The American biologist Sewall Wright, who had a background in animal breeding experiments, focused on combinations of interacting genes, and the effects of inbreeding on small, relatively isolated populations that exhibited genetic drift. In 1932, Wright introduced the concept of an adaptive landscape and argued that genetic drift and inbreeding could drive a small, isolated sub-population away from an adaptive peak, allowing natural selection to drive it towards different adaptive peaks. Fisher and Wright had some fundamental disagreements and a

controversy about the relative roles of selection and drift continued for much of the century between the Americans and the British. The Frenchman Gustave Malécot was also important early in the development of the discipline.

The work of Fisher, Haldane and Wright founded the discipline of *population genetics*. This integrated natural selection with Mendelian genetics, which was the critical first step in developing a unified theory of how evolution worked.[46] [47]

John Maynard Smith was Haldane's pupil, whilst W.D. Hamilton was heavily influenced by the writings of Fisher. The American George R. Price worked with both Hamilton and Maynard Smith. American Richard Lewontin and Japanese Motoo Kimura were heavily influenced by Wright.

Modern evolutionary synthesis

In the first few decades of the 20th century, most field naturalists continued to believe that Lamarckian and orthogenic mechanisms of evolution provided the best explanation for the complexity they observed in the living world. However, as the field of genetics continued to develop, those views became less tenable.[48] Theodosius Dobzhansky, a postdoctoral worker in T. H. Morgan's lab, had been influenced by the work on genetic diversity by Russian geneticists such as Sergei Chetverikov. He helped to bridge the divide between the foundations of microevolution developed by the population geneticists and the patterns of macroevolution observed by field biologists, with his 1937 book *Genetics and the Origin of Species*.

Dobzhansky examined the genetic diversity of wild populations and showed that, contrary to the assumptions of the population geneticists, these populations had large amounts of genetic diversity, with marked differences between sub-populations. The book also took the highly mathematical work of the population geneticists and put it into a more accessible form. In Great Britain E.B. Ford, the pioneer of ecological genetics, continued throughout the 1930s and 1940s to demonstrate the power of selection due to ecological factors including the ability to maintain genetic diversity through genetic polymorphisms such as human blood types. Ford's work would contribute to a shift in emphasis during the course of the modern synthesis towards natural selection over genetic drift.[46] [47] [49] [50]

See also

- Coalescent theory
- Dual inheritance theory
- Ecological genetics
- Evolutionarily Significant Unit
- Ewens's sampling formula
- Fitness landscape
- Founder effect
- Genetic diversity
- Genetic drift
- Genetic erosion
- Genetic pollution
- Gene pool
- Genotype-phenotype distinction
- Habitat fragmentation
- Hardy-Weinberg principle
- Microevolution
- Molecular evolution
- Muller's ratchet
- Mutational meltdown
- Neutral theory of molecular evolution

- Population bottleneck
- Quantitative genetics
- Reproductive compensation
- Selection
- Small population size
- Viral quasispecies

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External links

- Yale University (http://alfred.med.yale.edu/alfred/)
- EHSTRAFD.org - Earth Human STR Allele Frequencies Database (http://www.ehstrafd.org)
- History of population genetics (http://www.esp.org/books/sturt/history/contents/sturt-history-ch-17.pdf)
- National Geographic: Atlas of the Human Journey (https://www5.nationalgeographic.com/genographic/atlas.html) (Haplogroup-based human migration maps)
- Monash Virtual Laboratory (http://vlab.infotech.monash.edu.au/simulations/cellular-automata/population-genetics/) - Simulations of habitat fragmentation and population genetics online at Monash University's Virtual Laboratory.

Theoretical ecology

Theoretical ecology refers to several intellectual traditions. The tradition pursued in universities and scientific journals under the rubric of theoretical ecology addresses the equations and probability distributions that govern the demography and biogeography of species. Common topics of theoretical ecology include population dynamics and especially the mathematics of food webs, and competition.

To a large extent theoretical ecology draws on the work of G. Evelyn Hutchinson and his students. Brothers H.T. Odum and E.P. Odum are seen as the true founders of modern theoretical ecology (sometimes described as **ecosystem ecology**). Robert MacArthur brought theory to community ecology. Daniel Simberloff was the student of E.O. Wilson, with whom MacArthur collaborated on *The Theory of Island Biogeography*, a seminal work in the development of theoretical ecology. Simberloff went on to add rigour to experimental ecology and was one of the stalwarts in the SLOSS Debate (whether it is preferable to protect a **S**ingle **L**arge **o**r **S**everal **S**mall reserves) and forced supporters of Jared Diamond's community assembly rules to defend their ideas through Neutral Model Analysis. Simberloff also played a key role in the (ongoing) debate on the utility of corridors for connecting isolated reserves (with Reed Noss taking the lead on the opposing side).

MacArthur's students Stephen Hubbell and Michael Rosenzweig combined theoretical and practical elements into works that extended MacArthur and Wilson's Island Biogeography Theory - Hubbell with his Unified Neutral Theory of Biodiversity and Biogeography and Rosenzweig with is Species Diversity in Space and Time.

Other key theoretical ecologists include Robert May, Robert Rosen, author of "Life Itself", G. David Tilman, and Robert Ulanowicz, author of *Ecology: The Ascendant Perspective*.

Theoretical Ecologists

- G. Evelyn Hutchinson
- Robert MacArtur
- Edward O. Wilson
- Simon Levin
- Richard Levins
- Robert May
- George Sugihara
- Joel Cohen
- Robert V. ONeill
- Howard T. Odum
- Donald DeAngelis
- G. David Tilman
- Robert Ulanowicz

See also

- Ecosystem model
- Mathematical biology
- Population dynamics
- Population modeling
- Theoretical biology

Population dynamics

Population dynamics is the branch of life sciences that studies short- and long-term changes in the size and age composition of populations, and the biological and environmental processes influencing those changes. Population dynamics deals with the way populations are affected by birth and death rates, and by immigration and emigration, and studies topics such as aging populations or population decline.

History

Population dynamics has traditionally been the dominant branch of mathematical biology, which has a history of more than 210 years, although more recently the scope of mathematical biology has greatly expanded. The first principle of population dynamics is widely regarded as the exponential law of Malthus, as modelled by the Malthusian growth model. The early period was dominated by demographic studies such as the work of Benjamin Gompertz and Pierre François Verhulst in the early 19th century, who refined and adjusted the Malthusian demographic model.

A more general model formulation was proposed by F.J. Richards in 1959, further expanded by Simon Hopkins, in which the models of Gompertz, Verhulst and also Ludwig von Bertalanffy are covered as special cases of the general formulation. The Lotka–Volterra predator-prey equations are another famous example. The computer game SimCity and the MMORPG Ultima Online, among others, tried to simulate some of these population dynamics.

In the past 30 years, population dynamics has been complemented by evolutionary game theory, developed first by John Maynard Smith. Under these dynamics, evolutionary biology concepts may take a deterministic mathematical form. Population dynamics overlap with another active area of research in mathematical biology: mathematical epidemiology, the study of infectious disease affecting populations. Various models of viral spread have been proposed and analysed, and provide important results that may be applied to health policy decisions.

Fisheries and wildlife management

In fisheries and wildlife management, population is affected by three dynamic rate functions.

- Natality or birth rate, often recruitment, which means reaching a certain size or reproductive stage. Usually refers to the age a fish can be caught and counted in nets
- Population growth rate, which measures the growth of individuals in size and length. More important in fisheries, where population is often measured in biomass.
- Mortality, which includes harvest mortality and natural mortality. Natural mortality includes non-human predation, disease and old age.

If N_1 is the number of individuals at time 1 then

$$N_1 = N_0 + B - D + I - E$$

where N_0 is the number of individuals at time 0, B is the number of individuals born, D the number that died, I the number that immigrated, and E the number that emigrated between time 0 and time 1.

If we measures these rates over many time intervals, we can determine how a population's density changes over time. Immigration and emigration are present, but are usually not measured.

All of these are measured to determine the harvestable surplus, which is the number of individuals that can be harvested from a population without affecting long term stability, or average population size. The harvest within the harvestable surplus is considered compensatory mortality, where the harvest deaths are substituting for the deaths that would occur naturally. It started in Europe. Harvest beyond that is additive mortality, harvest in addition to all the animals that would have died naturally. These terms are not the universal good and evil of population management, for example, in deer, the DNR are trying to reduce deer population size overall to an extent, since hunters have reduced buck competition and increased deer population unnaturally.

Intrinsic rate of increase

The rate at which a population increases in size, i.e. the change in population size over a particular period of time is known as the *intrinsic rate of increase*. The concept is commonly used in insect population biology to determine how environmental factors affect the rate at which pest populations increase.[1]

See also

- Lotka–Volterra equation
- Minimum viable population
- Maximum sustainable yield
- Nicholson-Bailey model
- Nurgaliev's law
- Population cycle
- Population ecology
- Population genetics
- Population modeling
- Ricker model
- Societal collapse
- System dynamics
- Population dynamics of fisheries

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- Introduction to Social Macrodynamics: Compact Macromodels of the World System Growth by Andrey Korotayev, Artemy Malkov, and Daria Khaltourina. ISBN 5-484-00414-4
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External links

- GreenBoxes code sharing network (http://iugo-cafe.org/greenboxes). Greenboxes (Beta) is a repository for open-source population modelling and PVA code. Greenboxes allows users an easy way to share their code and to search for others shared code.
- The Virtual Handbook on Population Dynamics (http://www.thomas-brey.de/science/virtualhandbook). An online compilation of state-ot-the-art basic tools for the analysis of population dynamics with emphasis on benthic invertebrates.
- Creatures! (http://www/.futureskill.com) High School interactive simulation program that implements an agent based simulation of grass, rabbits and foxes.

Ecology

The scientific discipline of **ecology** encompasses areas from global processes (above), to the study of marine and terrestrial habitats (middle) to interspecific interactions such as predation and pollination (below).

Ecology (from Greek: οἶκος, "house" or "living relations"; -λογία, "study of") is the interdisciplinary scientific study of the distributions, abundance and relations of organisms and their interactions with the environment.[1] Ecology is also the study of ecosystems. Ecosystems describe the web or network of relations among organisms at different scales of organization. Since ecology refers to any form of biodiversity, ecologists research everything from tiny bacteria's role in nutrient recycling to the effects of tropical rain forest on the Earth's atmosphere. The discipline of ecology emerged from the natural sciences in the late 19th century. Ecology is not synonymous with environment, environmentalism, or environmental science.[1] [2] [3] Ecology is closely related to the disciplines of physiology, evolution, genetics and behavior.[4]

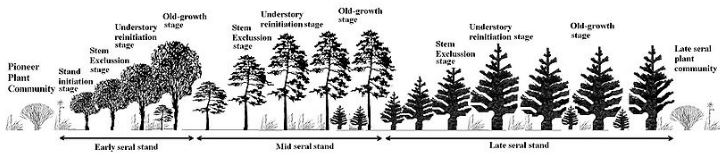
Like many of the natural sciences, a conceptual understanding of ecology is found in the broader details of study, including:

- life processes explaining adaptations
- distribution and abundance of organisms
- the movement of materials and energy through living communities
- the successional development of ecosystems, and
- the abundance and distribution of biodiversity in context of the environment.[1] [2] [3]

Ecology is distinguished from natural history, which deals primarily with the descriptive study of organisms. It is a sub-discipline of biology, which is the study of life.

There are many practical applications of ecology in conservation biology, wetland management, natural resource management (agriculture, forestry , fisheries), city planning (urban ecology), community health, economics, basic & applied science and it provides a conceptual framework for understanding and researching human social interaction (human ecology).[5] [6] [7] [8]

Levels of organization and study



Ecosystems regenerate after a disturbance such as fire, forming mosaics of different age groups structured across a landscape. Pictured are different seral stages in forested ecosystems starting from pioneers colonizing a disturbed site and maturing in successional stages leading to old-growth forests.

Because ecology deals with ever-changing ecosystems, both time and space must be considered when describing ecological phenomena.[9] In regards to time, it can take thousands of years for ecological processes to mature. The life-span of a tree, for example, can include different successional or seral stages leading to mature old-growth forests. The ecological process is extended even further through time as trees topple over and decay.

Ecosystems are also classified at different spatial scales: the area of an ecosystem can vary greatly from tiny to vast. For instance, several generations of an aphid population and their predators might exist on a single leaf. Inside each of those aphids exist diverse communities of bacteria.[10] The scale of study must at times be quite large, when studying the life of the tree in the forest where bacteria and aphids live.[11] To understand tree growth, for example, soil type, moisture content, slope of the land, forest canopy closure, and other local site variables must all be examined; to understand the ecology of the forest, complex global factors such as climate must be considered.[12]

Long-term ecological studies provide important track records to better understand ecosystems over space and time. The International Long Term Ecological Network[13] manages and exchanges scientific information among research sites. The longest experiment in existence is the Park Grass Experiment that was initiated in 1856.[14] Another example includes the Hubbard Brook study in operation since 1960.[15] Ecology is also complicated by the fact that small scale patterns do not necessarily explain large scale phenomena, otherwise captured in the expression 'the sum is greater than the parts'.[16] [17] These emergent phenomena operate at different environmental scales of influence, ranging from molecular to planetary scales, and require different sets of scientific explanation.[18] [19]

To structure the study of ecology into a manageable framework of understanding, the biological world is conceptually organized as a nested hierarchy of organization, ranging in scale from genes, to cells, to tissues, to organs, to organisms, to species and up to the level of the biosphere.[20] Ecosystems are primarily researched at (but not restricted to) three key levels of organization, including organisms, populations, and communities. Ecologists study ecosystems by sampling a certain number of individuals that are representative of a population. Ecosystems consist of communities interacting with each other and the environment. In ecology, communities are created by the interaction of the populations of different species in an area.[21] [22]

Biodiversity is an attribute of a site or area that consists of the variety within and among biotic communities, whether influenced by humans or not, at any spatial scale from microsites and habitat patches to the entire biosphere.[23] :745

Biodiversity (an amalgamation of the words biological diversity) describes all varieties of life from genes to ecosystems and spans every level of biological organization. There are many ways to index, measure, and represent biodiversity.[24] Biodiversity includes species diversity, ecosystem diversity, genetic diversity and the complex processes operating at and among these respective levels.[24] [25] [26] Biodiversity plays an important role in ecological health as much as it does for human health.[27] [28] Preventing or prioritizing species extinctions is one

way to preserve biodiversity, but populations, the genetic diversity within them and ecological processes, such as migration, are being threatened on global scales and disappearing rapidly as well. Conservation priorities and management techniques require different approaches and considerations to address the full ecological scope of biodiversity. Populations and species migration, for example, are more sensitive indicators of ecosystem services that sustain and contribute natural capital toward the well-being of humanity.[29] [30] [31] [32] An understanding of biodiversity has practical application for ecosystem-based conservation planners as they make ecologically responsible decisions in management recommendations to consultant firms, governments and industry.[33]

Ecological niche

Termite mounds with varied heights of chimneys regulate gas exchange, temperature and other environmental parameters that are needed to sustain the internal physiology of the entire colony.[34] [35]

The ecological niche is a central concept in the ecology of organisms. There are many definitions of the niche dating back to 1917,[36] but George Evelyn Hutchinson made conceptual advances in 1957[37] [38] and introduced the most widely accepted definition: "The niche is the set of biotic and abiotic conditions in which a species is able to persist and maintain stable population sizes."[36] :519 The ecological niche is divided into the *fundamental* and the *realized* niche. The fundamental niche is the set of environmental conditions under which a species is able to persist. The realized niche is the set of environmental plus ecological conditions under which a species is able to persist.[21] [36] [38] Organisms have functional traits that are uniquely adapted to the ecological niche. A trait is a measurable property of an organism that strongly influences its performance.[39] Biogeographical patterns and range distributions are explained or predicted through knowledge and understanding of a species niche requirements.[40] For example, the uniquely adapted nature of each species to their ecological niche means that they are able to competitively exclude other similarly adapted species from having an overlapping geographic range. This is called the competitive exclusion principle.[41] Important to the concept of niche is habitat. The habitat describes the environment over which a species is known to occur and the type of community that is formed as a result.[42] For example, habitat might refer to an aquatic or terrestrial environment that can be further categorized as montane or alpine ecosystems.

Biodiversity of a coral reef. Corals adapt and modify their environment by forming calcium carbonate skeletons that provide growing conditions for future generations and form habitat for many other species.[43]

Organisms are subject to environmental pressures, but they are also modifiers of their habitats. The regulatory feedback between organisms and their environment can modify conditions from local (e.g., a pond) to global scales (e.g., Gaia) and over time and even after death, such as decaying logs or silica skeleton deposits from marine organisms.[44] This process of ecosystem engineering has also been called niche construction. Ecosystem engineers are defined as: "...organisms that directly or indirectly modulate the availability of resources to other species, by causing physical state changes in biotic or abiotic materials. In so doing they modify, maintain and create habitats."[45] :373

The ecological engineering concept has stimulated a new appreciation for the degree of influence that organisms have on the ecosystem and evolutionary process. The niche construction concept highlights a previously underappreciated feedback mechanism of natural selection imparting forces on the abiotic niche.[34] [46] An example of natural selection through ecosystem engineering occurs in the nests of social insects, including ants, bees, wasps, and termites. There is an emergent homeostasis in the structure of the nest that regulates, maintains and defends the physiology of the entire colony. Termite mounds, for example, maintain a constant internal temperature through the design of air-conditioning chimneys. The structure of the nests themselves are subject to the forces of natural selection. Moreover, the nest can survive over successive generations, which means that ancestors inherit both genetic material and a legacy niche that was constructed before their time.[34] [35] [47]

Population ecology

The population is the unit of analysis in population ecology. A population consists of individuals of the same species that live, interact and migrate through the same niche and habitat.[48] A primary law of population ecology is the Malthusian growth model.[49] This law states that:

"...a population will grow (or decline) exponentially as long as the environment experienced by all individuals in the population remains constant."[49] :18

This Malthusian premise provides the basis for formulating predictive theories and tests that follow. Simplified population models usually start with four variables including death, birth, immigration, and emigration. Mathematical models are used to calculate changes in population demographics using a null model. A null model is used as a null hypothesis for statistical testing. The null hypothesis states that random processes create observed patterns. Alternatively the patterns differ significantly from the random model and require further explanation. Models can be mathematically complex where "...several competing hypotheses are simultaneously confronted with the data."[50] An example of an introductory population model describes a closed population, such as on an island, where immigration and emigration does not take place. In these island models the per capita rates of change are described as:

$$dN/dT = B - D = bN - dN = (b - d)N = rN\,,$$

where N is the total number of individuals in the population, B is the number of births, D is the number of deaths, b and d are the per capita rates of birth and death respectively, and r is the per capita rate of population change. This formula can be read out as the rate of change in the population (dN/dT) is equal to births minus deaths (B − D).[49] [51]

Using these modelling techniques, Malthus' population principle of growth was later transformed into a model known as the logistic equation:

$$dN/dT = aN(1 - N/K),$$

where N is the number of individuals measured as biomass density, a is the maximum per-capita rate of change, and K is the carrying capacity of the population. The formula can be read as follows: the rate of change in the population (dN/dT) is equal to growth (aN) that is limited by carrying capacity $(1 - N/K)$. The discipline of population ecology builds upon these introductory models to further understand demographic processes in real study populations and conduct statistical tests. The field of population ecology often uses data on life history and matrix algebra to develop projection matrices on fecundity and survivorship. This information is used for managing wildlife stocks and setting harvest quotas.[51] [52]

A list of terms that define various types of natural groupings of individuals that are used in population studies[53]

Term	Definition
Species population	All individuals of a species.
Metapopulation	A set of spatially disjunct populations, among which there is some immigration.
Population	A group of conspecific individuals that is demographically, genetically, or spatially disjunct from other groups of individuals.
Aggregation	A spatially clustered group of individuals.
Deme	A group of individuals more genetically similar to each other than to other individuals, usually with some degree of spatial isolation as well.
Local population	A group of individuals within an investigator-delimited area smaller than the geographic range of the species and often within a population (as defined above). A local population could be a disjunct population as well.
Subpopulation	An arbitrary spatially-delimited subset of individuals from within a population (as defined above).

r/K-Selection theory

A important concept in population ecology is *r/K*-selection theory. The concept was introduced in 1967 in a book entitled *The Theory of Island Biogeography* and was one of the first predictive models to explain life-history evolution. The premise behind this model is that forces of natural selection change according to the density of the population. When an island is first colonized, the density of individuals is low and the population size increases with reduced levels of competition and an abundance of available resources. Under such circumstances a population experiences density independent forces of natural selection, which is called *r*-selection. When the population becomes crowded, it reaches the island's carrying capacity, and individuals compete more heavily for limited resources. Under crowded conditions the population experiences density-dependent forces of natural selection, called *K*-selection.[54]

In the *r/K*-selection model, the first variable *r* is the intrinsic rate of natural increase in population size and the second variable *K* is the carrying capacity of a population.[21] Different species evolve different life-history strategies spanning a continuum between these two selective forces. An *r*-selected species is one that has high birth rates, low levels of parental investment, and high rates of mortality before individuals reach maturity. Evolution favors high rates of fecundity in *r*-selected species. Many kinds of insects and invasive species exhibit *r*-selected characteristics. In contrast, a *K*-selected species has low rates of fecundity, high levels of parental investment in the young, and low rates of mortality as individuals mature. Humans and elephants are examples of species exhibiting *K*-selected characteristics, including longevity and efficiency in the conversion of more resources into fewer offspring.[55] [56]

Metapopulation ecology

Populations are also studied and conceptualized through the metapopulation concept. The metapopulation concept was introduced in 1969[57] :"as a population of populations which go extinct locally and recolonize."[58] :105 Metapopulation ecology is another statistical approach that is often used in conservation research.[59] Metapopulation research simplifies the landscape into patches of varying levels of quality.[60] Like the r/K-selection model, metapopulation models have also been used to explain life-history evolution, such as the ecological stability of amphibian metamorphosis shifting life stages out of aquatic patches and into terrestrial patches.[61] In metapopulation terminology there are emigrants (individuals that leave a patch), immigrants (individuals that move into a patch) and sites are classed either as sources or sinks. A site is a generic term that refers to places where ecologists sample populations, such as ponds or defined sampling areas in a forest. Source patches are productive sites that generate a seasonal supply of juveniles that migrate to other patch locations. Sink patches are unproductive sites that only receive migrants and will go extinct unless rescued by an adjacent source patch or environmental conditions become more favorable. Metapopulation models examine patch dynamics over time to answer questions about spatial and demographic ecology. The ecology of metapopulations is a dynamic process of extinction and colonization. Small patches of lower quality (i.e., sinks) are maintained or rescued by a seasonal influx of new immigrants. A dynamic metapopulation structure evolves from year to year, where some patches are sinks in dry years and become sources when conditions are more favorable. Ecologists use a mixture of computer models and field studies to explain metapopulation structure.[62] [63]

Community ecology

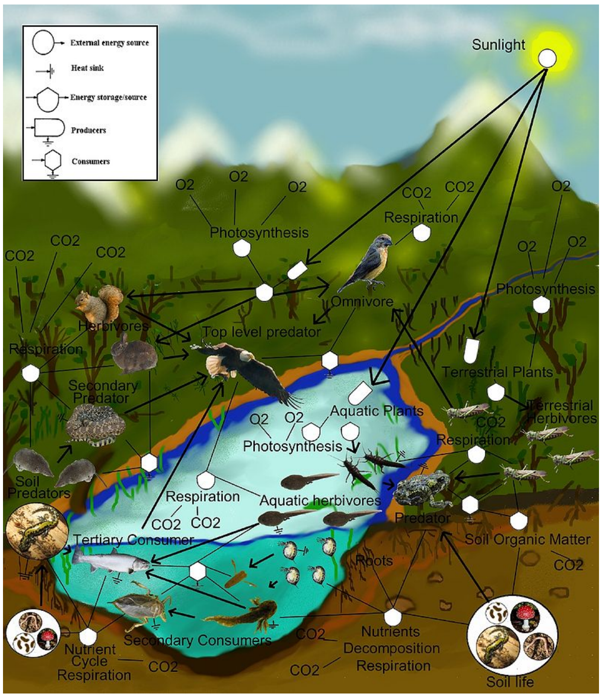
Community ecology examines how interactions among species and their environment affect the abundance, distribution and diversity of species within communities.

Johnson & Stinchcomb[64] :250

Community ecology is a subdiscipline of ecology which studies the distribution, abundance, demography, and interactions between coexisting populations. An example of a study in community ecology might measure primary production in a wetland in relation to decomposition and consumption rates. This requires an understanding of the community connections between plants (i.e., primary producers) and the decomposers (e.g., fungi and bacteria).[65] or the analysis of predator-prey dynamics affecting amphibian biomass.[66] Food webs and trophic levels are two widely employed conceptual models used to explain the linkages among species.[67] [68]

Food webs

Food webs are a type of concept map that illustrate ecological pathways, usually starting with solar energy being used by plants during photosynthesis. As plants grow, they accumulate carbohydrates and are eaten by grazing herbivores. Step by step lines or relations are drawn until a web of life is illustrated.[69] [70] [71] [72]



Freshwater aquatic and terrestrial food-webs

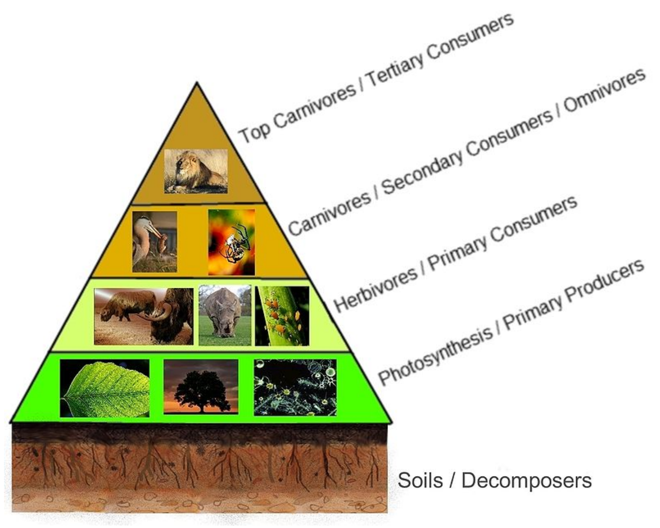
There are different ecological dimensions that can be mapped to create more complicated food webs, including: species composition (type of species), richness (number of species), biomass (the dry weight of plants and animals), productivity (rates of conversion of energy and nutrients into growth), and stability (food webs over time). A food web diagram illustrating species composition shows how change in a single species can directly and indirectly influence many others. Microcosm studies are used to simplify food web research into semi-isolated units such as small springs, decaying logs, and laboratory experiments using organisms that reproduce quickly, such as daphnia feeding on algae grown under controlled environments in jars of water.[73] [74]

Principles gleaned from food web microcosm studies are used to extrapolate smaller dynamic concepts to larger systems.[74] Food webs are limited because they are generally restricted to a specific habitat, such as a cave or a pond. The food web illustration (right) only shows a small part of the complexity connecting the aquatic system to the adjacent terrestrial land. Many of these species migrate into other habitats to distribute their effects on a larger scale. In other words, food webs are incomplete, but are nonetheless a valuable tool in understanding community ecosystems.[75]

Food chain length is another way of describing food webs as a measure of the number of species encountered as energy or nutrients move from the plants to top predators.[76] :269 There are different ways of calculating food chain length depending on what parameters of the food web dynamic are being considered: connectance, energy, or interaction.[76] In a simple predator-prey example, a deer is one step removed from the plants it eats (chain length = 1) and a wolf that eats the deer is two steps removed (chain length = 2). The relative amount or strength of influence that these parameters have on the food web address questions about:

- the identity or existence of a few dominant species (called strong interactors or keystone species)
- the total number of species and food-chain length (including many weak interactors) and
- how community structure, function and stability is determined.[74]

Trophic dynamics



A stylized image of a trophic pyramid with soil illustrated at the base

The Greek root of the word *troph*, τροφή, trophē, means food or feeding. Links in food-webs primarily connect feeding relations or trophism among species. Biodiversity within ecosystems can be organized into vertical and horizontal dimensions. The vertical dimension represents feeding relations that become further removed from the base of the food chain up toward top predators. The horizontal dimension represents the abundance or biomass at each level.[77] When the relative abundance or biomass of each functional feeding group is stacked into their respective trophic levels they naturally sort into a 'pyramid of numbers'.[78] Functional groups are broadly categorized as autotrophs (or primary producers), heterotrophs (or consumers), and detrivores (or decomposers). Heterotrophs can be further sub-divided into different functional groups, including: primary consumers (strict herbivores), secondary consumers (predators that feed exclusively on herbivores) and tertiary consumers (predators that feed on a mix of herbivores and predators).[79] Omnivores do not fit neatly into a functional category because they eat both plant and animal tissues. It has been suggested, however, that omnivores have a greater functional influence as predators because relative to herbivores they are comparatively inefficient at grazing.[80]

Ecologist collect data on trophic levels and food webs to statistically model and mathematically calculate parameters, such as those used in other kinds of network analysis (e.g., graph theory), to study emergent patterns and properties shared among ecosystems. The emergent pyramidal arrangement of trophic levels with amounts of energy transfer decreasing as species become further removed from the source of production is one of several patterns that is repeated amongst the planets ecosystems.[72] [81] [82] The size of each level in the pyramid generally represents biomass, which can be measured as the dry weight of an organism.[83] Autotrophs may have the highest global proportion of biomass, but they are closely rivaled or surpassed by microbes.[84] [85]

The decomposition of dead organic matter, such as leaves falling on the forest floor, turns into soils that feed plant production. The total sum of the planet's soil ecosystems is called the pedosphere where a very large proportion of the Earth's biodiversity sorts into other trophic levels. Invertebrates that feed and shred larger leaves, for example, create smaller bits for smaller organisms in the feeding chain. Collectively, these are the detrivores that regulate soil formation.[86] [87] Tree roots, fungi, bacteria, worms, ants, beetles, centipedes, spiders, mammals, birds, reptiles, amphibians and other less familiar creatures all work to create the trophic web of life in soil ecosystems. As organisms feed and migrate through soils they physically displace materials, which is an important ecological process called bioturbation. Biomass of soil microorganisms are influenced by and feed back into the trophic dynamics of the exposed solar surface ecology. Paleoecological studies of soils places the origin for bioturbation to a time before the Cambrian period. Other events, such as the evolution of trees and amphibians moving into land in the Devonian period played a significant role in the development of soils and ecological trophism.[66] [87] [88]

List of ecological functional groups, definitions and examples

Functional Group	Definition and Examples
Producers or *Autotrophs*	Usually plants or cyanobacteria that are capable of photosynthesis but could be other organisms such as the bacteria near ocean vents that are capable of chemosynthesis.
Consumers or *Heterotrophs*	Animals, which can be primary consumers (herbivorous), or secondary or tertiary consumers (carnivorous and omnivores).
Decomposers or *Detritivores*	Bacteria, fungi, and insects which degrade organic matter of all types and restore nutrients to the environment. The producers will then consume the nutrients, completing the cycle.

Functional trophic groups sort out hierarchically into pyramidic trophic levels because it requires specialized adaptations to become a photosynthesizer or a predator, so few organisms have the adaptations needed to combine both abilities. This explains why functional adaptations to trophism (feeding) organizes different species into emergent functional groups.[80] Trophic levels are part of the holistic or complex systems view of ecosystems.[89] [90] Each trophic level contains unrelated species that grouped together because they share common ecological functions. Grouping functionally similar species into a trophic system gives a macroscopic image of the larger functional design.[91]

Links in a food-web illustrate direct trophic relations among species, but there are also indirect effects that can alter the abundance, distribution, or biomass in the trophic levels. For example, predators eating herbivores indirectly influence the control and regulation of primary production in plants. Although the predators do not eat the plants directly, they regulate the population of herbibores that are directly linked to plant trophism. The net effect of direct and indirect relations is called trophic cascades. Trophic cascades are separated into species-level cascades, where only a subset of the food-web dynamic is impacted by a change in population numbers, and community-level cascades, where a change in population numbers has a dramatic effect on the entire food-web, such as the distribution of plant biomass.[92]

Keystone species

A keystone species is a species that is disproportionately connected to more species in the food-web. Keystone species have lower levels of biomass in the trophic pyramid relative to the importance of their role. The many connections that a keystone species holds means that it maintains the organization and structure of entire communities. The loss of a keystone species results in a range of dramatic cascading effects that alters trophic dynamics, other food-web connections and can cause the extinction of other species in the community.[93] [94]

Sea otters (*Enhydra lutris*) are commonly cited as an example of a keystone species because they limit the density of sea urchins that feed on kelp. If sea otters are removed from the system, the urchins graze until the kelp beds disappear and this has a dramatic effect on community structure.[95] Hunting of sea otters, for example, is thought to have indirectly lead to the extinction of the Steller's Sea Cow (*Hydrodamalis gigas*).[96] While the keystone species concept has been used extensively as a conservation tool, it has been criticized for being poorly defined from an operational stance. It is very difficult to experimentally determine in each different ecosystem what species may hold a keystone role. Furthermore, food-web theory suggests that keystone species may not be all that common. It is therefore unclear how generally the keystone species model can be applied.[92] [95]

Biome and biosphere

Ecological units of organization are defined through reference to any magnitude of space and time on the planet. Communities of organisms, for example, are somewhat arbitrarily defined, but the processes of life integrate at different levels and organize into more complex wholes. Biomes, for example, are a larger unit of organization that categorize regions of the Earth's ecosystems mainly according to the structure and composition of vegetation.[97] Different researchers have applied different methods to define continental boundaries of biomes dominated by

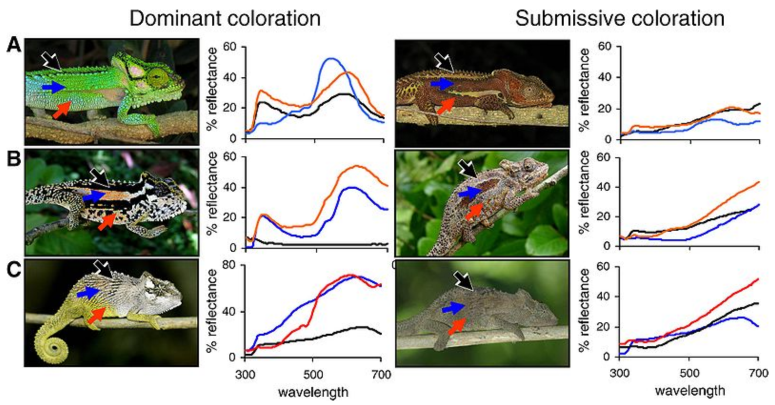
different functional types of vegetative communities that are limited in distribution by climate, precipitation, weather and other environmental variables. Examples of biome names include: tropical rainforest, temperate broadleaf and mixed forests, temperate deciduous forest, taiga, tundra, hot desert, and polar desert.[98] Other researchers have recently started to categorize other types of biomes, such as the human and oceanic microbiomes. To a microbe, the human body is a habitat and a landscape.[99] The microbiome has been largely discovered through advances in molecular genetics that have revealed a hidden richness of microbial diversity on the planet. The oceanic microbiome plays a significant role in the ecological biogeochemistry of the planet's oceans.[100]

Ecological theory has been used to explain self-emergent regulatory phenomena at the planetary scale. The largest scale of ecological organization is the biosphere: the total sum of ecosystems on the planet. Ecological relations regulate the flux of energy, nutrients, and climate all the way up to the planetary scale. For example, the dynamic history of the planetary CO_2 and O_2 composition of the atmosphere has been largely determined by the biogenic flux of gases coming from respiration and photosynthesis, with levels fluctuating over time and in relation to the ecology and evolution of plants and animals.[101] When sub-component parts are organized into a whole there are oftentimes emergent properties that describe the nature of the system. This the Gaia hypothesis,[19] and is an example of holism applied in ecological theory.[102] The ecology of the planet acts as a single regulatory or holistic unit called Gaia. The Gaia hypothesis states that there is an emergent feedback loop generated by the metabolism of living organisms that maintains the temperature of the Earth and atmospheric conditions within a narrow self-regulating range of tolerance.[19]

Ecology and evolution

Ecology and evolution are considered sister disciplines of the life sciences. Natural selection, life history, development, adaptation, populations, and inheritance are examples of concepts that thread equally into ecological and evolutionary theory. Morphological, behavioural and/or genetic traits, for example, can be mapped onto evolutionary trees to study the historical development of a species in relation to their functions and roles in different ecological circumstances. In this framework, the analytical tools of ecologists and evolutionists overlap as they organize, classify and investigate life through common systematic principals, such as phylogenetics or the Linnaean system of taxonomy.[103] The two disciplines often appear together, such as in the title of the journal *Trends in Ecology and Evolution*.[104] There is no sharp boundary separating ecology from evolution and they differ more in their areas of applied focus. Both disciplines discover and explain emergent and unique properties and processes operating across different spatial or temporal scales of organization.[19] [105] [106] While the boundary between ecology and evolution is not always clear, it is understood that ecologists study the abiotic and biotic factors that influence the evolutionary process.[2] [83]

Behavioral ecology



Social display and color variation in differently adapted species of chameleons (*Bradypodion* spp.). Chameleons change their skin color to match their background as a behavioral defense mechanism and also use color to communicate with other members of their species, such as dominant (left) versus submissive (right) patterns shown in the three species (A-C) above.[107]

All organisms are motile to some extent. Behavioural ecology is the study of ethology and its ecological and evolutionary implications. Ethology is the study of observable movement or behaviour in nature. This could include investigations of motile sperm of plants and zooplankton swimming toward the female egg, the cultivation of fungi by weevils, the mating dance of a salamander, or social gatherings of amoeba.[108] [109] [110] [111] [112]

Adaptation is the central unifying concept in behavioral ecology."International Society for Behavioral Ecology" [113]. Behaviors can be recorded as traits and inherited in much the same way that eye and hair color can. Behaviours evolve and become adapted to the ecosystem because they are subject to the forces of natural selection.[25] Hence, behaviors can be adaptive, meaning that they evolve functional utilities that increases reproductive success for the individuals that inherit such traits.[114] This is also the technical definition for fitness in biology, which is a measure of reproductive success over successive generations.[25]

Predator-prey interactions are an introductory concept into food-web studies as well as behavioural ecology.[115] Prey species can exhibit different kinds of behavioural adaptations to predators, such as avoid, flee or defend. Many prey species are faced with multiple predators that differ in the degree of danger posed. To be adapted to their environment and face predatory threats, organisms must balance their energy budgets as they invest in different aspects of their life history, such as growth, feeding, mating, socializing, or modifying their habitat. Hypotheses posited in behavioural ecology are generally based on adaptive principals of conservation, optimization or efficiency.[1] [2] [3] [116] For example,

"The threat-sensitive predator avoidance hypothesis predicts that prey should assess the degree of threat posed by different predators and match their behavior according to current levels of risk."[117]

"The optimal flight initiation distance occurs where expected postencounter fitness is maximized, which depends on the prey’s initial fitness, benefits obtainable by not fleeing, energetic escape costs, and expected fitness loss due to predation risk."[118]

The behaviour of long-toed salamanders (*Ambystoma macrodactylum*) presents an example in this context. When threatened, the long-toed salamander defends itself by waving its tail and secreting a white milky fluid.[119] [120] The excreted fluid is distasteful, toxic and adhesive, but it is also used for nutrient and energy storage during hibernation. Hence, salamanders subjected to frequent predatory attack will be energetically compromised as they use up their energy stores.[121] [122]

Ecological interactions can be divided into host and associate relationships. A host is any entity that harbors another that is called the associate.[124] Host and associate relationships among species that are mutually or reciprocally beneficial are called mutualisms. If the host and associate are physically connected, the relationship is called symbiosis. Approximately 60% of all plants, for example, have a symbiotic relationship with arbuscular mycorrhizal fungi. Symbiotic plants and fungi exchange carbohydrates for mineral nutrients.[125] Symbiosis differs from indirect mutualisms where the organisms live apart. For example, tropical rainforests regulate the Earth's atmosphere. Trees living in the equatorial regions of the planet supply oxygen into the atmosphere that sustains species living in distant polar regions of the planet. This relationship is called commensalism because many other host species receive the benefits of clean air at no cost or harm to the associate tree species supplying the oxygen.[126] The host and associate relationship is called parasitism if one species benefits while the other suffers. Competition among species or among members of the same species is defined as reciprocal antagonism, such as grasses competing for growth space.[127]

Symbiosis: Leafhoppers (*Eurymela fenestrata*) are protected by ants (*Iridomyrmex purpureus*) in a symbiotic relationship. The ants protect the leafhoppers from predators and in return the leafhoppers feeding on plants exude honeydew from their anus that provides energy and nutrients to tending ants.[123]

Parasites: A harvestman spider is parasiticized by mites. This is parasitism because the spider suffers as its juices are slowly sucked out and the mites gain all the benefits of a host to travel on and feed off.

Popular ecological study systems for mutualism include, fungus-growing ants employing agricultural symbiosis, bacteria living in the guts of insects and other organisms, the fig wasp and yucca moth pollination complex, lichens with fungi and photosynthetic algae, and corals with photosynthetic algae.[128] [129]

Intraspecific behaviours are notable in the social insects, slime moulds, social spiders, human society, and naked mole rats where eusocialism has evolved. Social behaviours include reciprocally beneficial behaviours among kin and nest mates.[25] [110] [130] Social behaviours evolve from kin and group selection. Kin selection explains altruism through genetic relationships, whereby an altruistic behaviour leading to death is rewarded by the survival of genetic copies distributed among surviving relatives. The social insects, including ants, bees and wasps are most famously studied for this type of relationship because the male drones are clones that share the same genetic make-up as every other male in the colony.[25] In contrast, group selectionists find examples of altruism among non-genetic relatives and explain this through selection acting on the group, whereby it becomes selectively advantageous for groups if their members express altruistic behaviours to one another. Groups that are predominantely altruists beat groups that are predominantely selfish.[25] [131]

A often quoted behavioural ecology hypothesis is known as Lack's brood reduction hypothesis (named after David Lack). Lack's hypothesis posits an evolutionary and ecological explanation as to why birds lay a series of eggs with an asynchronous delay leading to nestlings of mixed age and weights. According to Lack, this brood behaviour is an ecological insurance that allows the larger birds to survive in poor years and all birds to survive when food is plentiful.[132] [133]

Elaborate sexual displays and posturing are encountered in the behavioural ecology of animals. The birds of paradise, for example, display elaborate ornaments and song during courtship. These displays serve a dual purpose of signalling healthy or well-adapted individuals and good genes. The elaborate displays are driven by sexual selection as an advertisement of quality of traits among male suitors.[134]

Biogeography

The word *biogeography* is an amalgamation of *biology* and *geography*. Biogeography is the comparative study of the geographic distribution of organisms and the corresponding evolution of their traits in space and time.[135] The Journal of Biogeography was established in 1974.[136] Biogeography and ecology share many of their disciplinary roots. For example, the theory of island biogeography, published by the mathematician Robert MacArthur and ecologist Edward O. Wilson in 1967[55] is considered one of the fundamentals of ecological theory.[137]

Biogeography has a long history in the natural sciences where questions arise concerning the spatial distribution of plants and animals. Ecology and evolution provide the explanatory context for biogeographical studies.[135] Biogeographical patterns result from ecological processes that influence range distributions, such as migration and dispersal.[137] and from historical processes that split populations or species into different areas.[138] The biogeographic processes that result in the natural splitting of species explains much of the modern distribution of the Earth's biota. The splitting of lineages in a species is called vicariance biogeography and it is a sub-discipline of biogeography.[138] [139] [140] There are also practical applications in the field of biogeography concerning ecological systems and processes. For example, the range and distribution of biodiversity and invasive species responding to climate change is a serious concern and active area of research in context of global warming.[30] [141]

Molecular Ecology

The important relationship between ecology and genetic inheritance predates modern techniques for molecular analysis. Molecular ecological research became more feasible with the development of genetic technologies, such as the polymerase chain reaction (PCR). The rise of molecular technologies and influx of research questions into this new ecological field resulted in the publication *Molecular Ecology* in 1992.[142] Molecular ecology uses various analytical techniques to study genes in an evolutionary and ecological context. In 1994, professor John Avise played a leading role in this area of science with the publication of his book, *Molecular Markers, Natural History and Evolution*.[143] Newer technologies opened a wave of genetic analysis into organisms once difficult to study from an ecological or evolutionary standpoint, such as bacteria, fungi and nematodes. Molecular ecology engendered a new research paradigm to investigate ecological questions considered otherwise intractable. Molecular ecology revealed previously obscured details in the intricacies of nature and improved resolution into probing questions about behavioral and biogeographical ecology. For example, molecular ecology revealed promiscuous sexual behavior and multiple male partners in tree swallows previously thought to be socially monogamous.[144] In a biogeographical context, the marriage between genetics, ecology and evolution resulted in a new sub-discipline called phylogeography.[145]

Ecology and the environment

"The environment of any organism is the class composed of the sum of those phenomena that enter a reaction system of the organism or otherwise directly impinge upon it to affect its mode of life at any time throughout its life cycle as ordered by the demands of the ontogeny of the organism or as ordered by any other condition of the organism that alters its environmental demands."

Mason et al.[146] :332

The environment is dynamically interlinked with ecology. Like the term ecology, environment has different conceptual meanings and to many these terms also overlap with the concept of *nature*. Environment "...includes the physical world, the social world of human relations and the built world of human creation."[147] :62 This section describes the physical environmental attributes or parameters that are external to the level of biological organization under investigation, including abiotic factors such as temperature, radiation, light, chemistry, climate and geology, and biotic factors, including genes, cells, organisms, members of the same species (conspecifics) and other species that share a habitat.[148] The physical environmental connection means that the laws of thermodynamics applies to ecology. Armed with an understanding of metabolic and thermodynamic principles a complete accounting of energy and material flow can be traced through an ecosystem.[149]

Environmental and ecological relations are studied through reference to conceptually manageable and isolated parts. However, once the effective environmental components are understood they conceptually link back together as a *holocoenotic*[150] system. In other words, the organism and the environment form a dynamic whole (or umwelt).[151] :252 Change in one ecological or environmental factor can concurrently affect the dynamic state of an entire ecosystem.[152] [153]

Ecological studies are necessarily holistic as opposed to reductionistic.[18] [154] Holism has three scientific meanings or uses that identify with: 1) the mechanistic complexity of ecosystems, 2) the practical description of patterns in quantitative reductionist terms where correlations may be identified but nothing is understood about the causal relations without reference to the whole system, which leads to 3) a metaphysical hierarchy whereby the causal relations of larger systems are understood without reference to the smaller parts. An example of the metaphysical aspect to holism is the trend of increased exterior thickness in shells of different species. The reason for a thickness increase can be understood through reference to principals of natural selection via predation without any reference to the biomolecular properties of the exterior shells.[155]

Metabolism and the early atmosphere

Metabolism – the rate at which energy and material resources are taken up from the environment, transformed within an organism, and allocated to maintenance, growth and reproduction – is a fundamental physiological trait.

Ernst et al.[156] :991

The Earth formed approximately 4.5 billion years ago[157] and environmental conditions were too extreme for life to form for the first 500 million years. During this early Hadean period, the Earth started to cool allowing time for a crust and oceans to form. Environmental conditions were unsuitable for the origins of life for the first billion years after the Earth formed. The Earth's atmosphere transformed from hydrogen dominant, to one composed mostly of methane and ammonia. Over the next billion years the metabolic activity of life transformed the atmosphere to higher concentrations of carbon dioxide, nitrogen, and water vapor. These gases changed the way that light from the sun hit the Earth's surface and greenhouse effects trapped in heat. There were untapped sources of free energy within the mixture of reducing and oxidizing gasses that set the stages for primitive ecosystems to evolve and, in turn, the atmosphere also evolved.[158]

The leaf is the primary site of photosynthesis in most plants.

Throughout history, the Earth's atmosphere and biogeochemical cycles has been in a dynamic equilibrium with planetary ecosystems. The history is characterized by periods of significant transformation followed by millions of years of stability.[159] The evolution of the earliest organisms, likely anaerobic methanogen microbes, started the process by converting atmospheric hydrogen into methane ($4H_2 + CO_2 \rightarrow CH_4 + 2H_2O$). Anoxygenic photosynthesis converting hydrogen sulfide into other sulfur compounds or water ($2H_2S + CO_2 \rightarrow h\nu \rightarrow CH_2O \rightarrow H_2O \rightarrow + 2S$ or $2H_2 + CO_2 + h\nu \rightarrow CH_2O + H_2O$), as occurs in deep sea hydrothermal vents today, reduced hydrogen concentrations and increased atmospheric methane. Early forms of fermentation also increased levels of atmospheric methane. The climatic history of Earth is characterized by a series of major transitions separated by long periods of relative stability. The transition to an oxygen dominant atmosphere (the *Great Oxidation*) did not begin until approximately 2.4-2.3 billion years ago, but photosynthetic processes started 0.3 to 1 billion years prior.[159] [160]

Radiation: heat, temperature and light

The biology of life operates within a certain range of temperatures. Heat is a form of energy that regulates temperature. Heat affects growth rates, activity, behavior and primary production. Temperature is largely dependent on the incidence of solar radiation. The latitudinal and longitudinal spatial variation of temperature greatly affects climates and consequently the distribution of biodiversity and levels of primary production in different ecosystems or biomes across the planet. Heat and temperature relate importantly to metabolic activity. Poikilotherms, for example, have a body temperature that is largely regulated and dependent on the temperature of the external environment. In

contrast, homeotherms regulate their internal body temperature by expending metabolic energy.[2] [83] [149]

There is a relationship between light, primary production, and ecological energy budgets. Sunlight is the primary input of energy into the planet's ecosystems. Light is composed of electromagnetic energy of different wavelengths. Radiant energy from the sun generates heat, provides photons of light measured as active energy in the chemical reactions of life, and also acts as a catalyst for genetic mutation.[2] [83] [149] Plants, algae, and some bacteria absorb light and assimilate the energy through photosynthesis. Organisms capable of assimilating energy by photosynthesis or through inorganic fixation of H_2S are autotrophs. Autotrophs—responsible for primary production—assimilate light energy that becomes metabolically stored as potential energy in the form of biochemical enthalpic bonds.[2] [83] [149]

Physical environments

Water

Wetland conditions such as shallow water, high plant productivity, and anaerobic substrates provide a suitable environment for important physical, biological, and chemical processes. Because of these processes, wetlands play a vital role in global nutrient and element cycles.:29[161]

The rate of diffusion of carbon dioxide and oxygen is approximately 10,000 times slower in water than it is in air. When soils become flooded, they quickly lose oxygen from low-concentration (hypoxic) to an (anoxic) environment where anaerobic bacteria thrive among the roots. Water also influences the spectral properties of light that becomes more diffuse as it is reflected off the water surface and submerged particles.[161] Aquatic plants exhibit a wide variety of morphological and physiological adaptations that allow them to survive, compete and diversify these environments. For example, the roots and stems develop large cellular air spaces to allow for the efficient transportation gases (for example, CO_2 and O_2) used in respiration and photosynthesis. In drained soil, microorganisms use oxygen during respiration. In aquatic environments, anaerobic soil microorganisms use nitrate, manganic ions, ferric ions, sulfate, carbon dioxide and some organic compounds. The activity of soil microorganisms and the chemistry of the water reduces the oxidation-reduction potentials of the water. Carbon dioxide, for example, is reduced to methane (CH_4) by methanogenic bacteria. Salt water also requires special physiological adaptations to deal with water loss. Salt water plants (or halophytes) are able to osmo-regulate their internal salt (NaCl) concentrations or develop special organs for shedding salt away.[161] The physiology of fish is also specially adapted to deal with high levels of salt through osmoregulation. Their gills form electrochemical gradients that mediate salt excrusion in salt water and uptake in fresh water.[162]

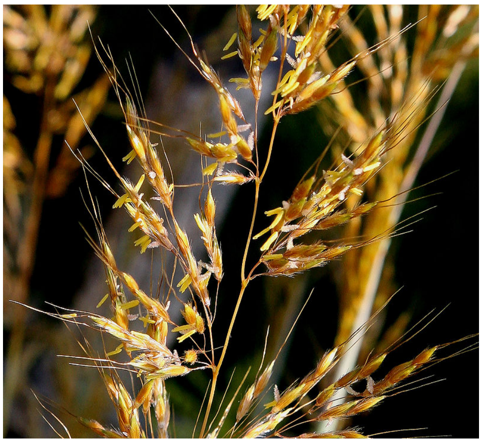
Gravity

The shape and energy of the land is affected to a large degree by gravitational forces. On a larger scale, the distribution of gravitational forces on the earth are uneven and influence the shape and movement of tectonic plates as well as having an influence on geomorphic processes such as orogeny and erosion. These forces govern many of the geophysical properties and distributions of ecological biomes across the Earth. On a organism scale, gravitational forces provide directional cues for plant and fungal growth (gravitropism), orientation cues for animal migrations, and influence the biomechanics and size of animals.[2] Ecological traits, such as allocation of biomass in trees during growth are subject to mechanical failure as gravitational forces influence the position and structure of branches and leaves.[163] The cardiovascular systems of all animals are functionally adapted to overcome pressure and gravitational forces that change according to the features of organisms (e.g., height, size, shape), their behavior (e.g., diving, running, flying), and the habitat occupied (e.g., water, hot deserts, cold tundra).[164]

Pressure

Climatic and osmotic pressure places physiological constraints on organisms, such as flight and respiration at high altitudes, or diving to deep ocean depths. These constraints influence vertical limits of ecosystems in the biosphere as organisms are physiologically sensitive and adapted to atmospheric and osmotic water pressure differences.[2] Oxygen levels, for example, decrease with increasing pressure and are a limiting factor for life at higher altitudes.[165] Water transportation through trees is another important ecophysiological parameter dependent upon pressure.[166] [167] Water pressure in the depths of oceans requires adaptations to deal with the different living conditions. Mammals, such as whales, dolphins and seals are adapted to deal with changes in sound due to water pressure differences.[168]

Wind and turbulence



The architecture of inflorescence in grasses is subject to the physical pressures of wind and shaped by the forces of natural selection facilitating wind-pollination (or anemophily).[169] [170]

Turbulent forces in air and water have significant effects on the environment and ecosystem distribution, form and dynamics. On a planetary scale, ecosystems are affected by circulation patterns in the global trade winds. Wind power and the turbulent forces it creates can influence heat, nutrient, and biochemical profiles of ecosystems.[2] For example, wind running over the surface of a lake creates turbulence, mixing the water column and influencing the environmental profile to create thermally layered zones, partially governing how fish, algae, and other parts of the aquatic ecology are structured.[171] [172] Wind speed and turbulence also exert influence on rates of evapotranspiration rates and energy budgets in plants and animals.[161] [173] Wind speed, temperature and moisture content can vary as winds travel across different landfeatures and elevations. The westerlies, for example, come into contact with the coastal and interior mountains of western North America to produce a rain shadow on the leeward side of the mountain. The air expands and moisture condenses as the winds move up in elevation which can cause precipitation; this is called orographic lift. This environmental process produces spatial divisions in biodiversity, as species adapted to wetter conditions are range-restricted to the coastal mountain valleys and unable to migrate across the xeric ecosystems of the Columbia Basin to intermix with sister lineages that are segregated to the interior mountain systems.[174] [175]

Fire

Forest fires modify the land by leaving behind an environmental mosaic that diversifies the landscape into different seral stages and habitats of varied quality (left). Some species are adapted to forest fires, such as pine trees that open their cones only after fire exposure (right).

Plants convert carbon dioxide into biomass and emit oxygen into the atmosphere.[176] Approximately 350 million years ago (near the Devonian period) the photosynthetic process brought the concentration of atmospheric oxygen above 17%, which allowed combustion to occur.[177] Fire releases CO_2 and converts fuel into ash and tar. Fire is a significant ecological parameter that raises many issues pertaining to its control and suppression in management.[178] While the issue of fire in relation to ecology and plants has been recognized for a long time,[179] Charles Cooper

brought attention to the issue of forest fires in relation to the ecology of forest fire suppression and management in the 1960s.[180] [181]

Fire creates environmental mosaics and a patchiness to ecosystem age and canopy structure. Native North Americans were among the first to influence fire regimes by controlling their spread near their homes or by lighting fires to stimulate the production of herbaceous foods and basketry materials.[182] The altered state of soil nutrient supply and cleared canopy structure also opens new ecological niches for seedling establishment.[183] [184] Most ecosystem are adapted to natural fire cycles. Plants, for example, are equipped with a variety of adaptations to deal with forest fires. Some species (e.g., *Pinus halepensis*) cannot germinate until after their seeds have lived through a fire. This environmental trigger for seedlings is called serotiny.[185] Some compounds from smoke also promote seed germination.[186]

Biogeochemistry

Ecologists study and measure nutrient budgets to understand how these materials are regulated and flow through the environment.[2] [83] [149] This research has led to an understanding that there is a global feedback between ecosystems and the physical parameters of this planet including minerals, soil, pH, ions, water and atmospheric gases. There are six major elements, including H (hydrogen), C (carbon), N (nitrogen), O (oxygen), S (sulfur), and P (phosphorus) that form the constitution of all biological macromolecules and feed into the Earth's geochemical processes. From the smallest scale of biology the combined effect of billions upon billions of ecological processes amplify and ultimately regulate the biogeochemical cycles of the Earth. Understanding the relations and cycles mediated between these elements and their ecological pathways has significant bearing toward understanding global biogeochemistry.[187]

The ecology of global carbon budgets gives one example of the linkage between biodiversity and biogeochemistry. For starters, the Earth's oceans are estimated to hold 40,000 gigatonnes (Gt) carbon, vegetation and soil is estimated to hold 2070 Gt carbon, and fossil fuel emissions are estimated to emit an annual flux of 6.3 Gt carbon.[188] At different times in the Earth's history there has been major restructuring in these global carbon budgets that was regulated to a large extent by the ecology of the land. For example, through the early-mid Eocene volcanic outgassing, the oxidation of methane stored in wetlands, and seafloor gases increased atmospheric CO_2 concentrations to levels as high as 3500 ppm.[189] In the Oligocene, from 25 to 32 million years ago, there was another significant restructuring in the global carbon cycle as grasses evolved a special type of C4 photosynthesis and expanded their ranges. This new photosynthetic pathway evolved in response to the drop in atmospheric CO_2 concentrations below 550 ppm.[190] Ecosystem functions such as these feed back significantly into global atmospheric models for carbon cycling. Loss in the abundance and distribution of biodiversity causes global carbon cycle feedbacks that are expected to increase rates of global warming in the next century.[191] The effect of global warming melting large sections of permafrost creates a new mosaic of flooded areas where decomposition results in the emission of methane (CH_4). Hence, there is a relationship between global warming, decomposition and respiration in soils and wetlands producing significant climate feedbacks and altered global biogeochemical cycles.[192] [193] There is concern over increases in atmospheric methane in the context of the global carbon cycle, because methane is also a greenhouse gas that is 23 times more effective at absorbing long-wave radiation on a 100 year time scale.[194]

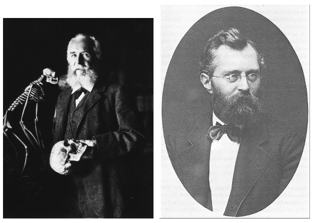
Historical roots of ecology

Unlike many of the scientific disciplines, ecology has a complex and winding origin due in large part to its interdisciplinary nature.[195] Several published books provide extensive coverage of the classics.[196] [197] In the early 20th century, ecology was an analytical form of natural history.[198] The descriptive nature of natural history included examination of the interaction of organisms with both their environment and their community. Such examinations were conducted by important natural historians including James Hutton and Jean-Baptiste Lamarck

contributed to the development of ecology.[199] The term "ecology" (German: *Oekologie*) is a more recent scientific development and was first coined by the German biologist Ernst Haeckel in his book *Generelle Morpologie der Organismen* (1866).

By ecology we mean the body of knowledge concerning the economy of nature-the investigation of the total relations of the animal both to its inorganic and its organic environment; including, above all, its friendly and inimical relations with those animals and plants with which it comes directly or indirectly into contact-in a word, ecology is the study of all those complex interrelations referred to by Darwin as the conditions of the struggle of existence.

Haeckel's definition quoted in Esbjorn-Hargens[200] :6

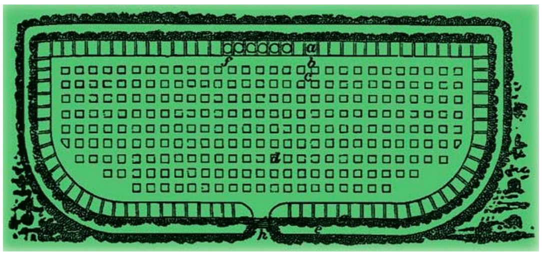


Ernst Haeckel (left) and Eugenius Warming (right), two early founders of ecology

Opinions differ on who was the founder of modern ecological theory. Some mark Haeckel's definition as the beginning,[201] others say it was Eugen Warming with the writing of Oecology of Plants: An Introduction to the Study of Plant Communities (1895).[202] Ecology may also be thought to have begun with Carl Linnaeus' research principals on the economy of nature that matured in the early 18th century.[69] [203] He founded an early branch of ecological study he called the economy of nature.[69] The works of Linnaeus influenced Darwin in *The Origin of Species* where he adopted the usage of Linnaeus' phrase on the *economy or polity of nature*.[204] Linnaeus made the first to attempt to define *the balance of nature*, which had previously been held as an assumption rather than formulated as a testable hypothesis. Haeckel, who admired Darwin's work, defined ecology in reference to the economy of nature which has lead some to question if ecology is synonymous with Linnaeus' concepts for the economy of nature.[203] Biogeographer Alexander von Humbolt was also foundational and was among the first to recognize ecological gradients and alluded to the modern ecological law of species to area relationships.[205] [206]

The modern synthesis of ecology is a young science, which first attracted substantial formal attention at the end of the 19th century (around the same time as evolutionary studies) and become even more popular during the 1960s environmental movement.[199] However, many observations, interpretations and discoveries relating to ecology extend back to much earlier studies in natural history. For example, the concept on the balance or regulation of nature can be traced back to Herodotos (died *c*. 425 BC) who described an early account of mutualism along the Nile river where crocodiles open their mouths to beneficially allow sandpipers safe access to remove leeches.[195] In the broader contributions to the historical development of the ecological sciences, Aristotle is considered one of the earliest naturalists who had an influential role in the philosophical development of ecological sciences. One of Aristotle's students, Theophrastus, made astute ecological observations about plants and posited a philosophical stance about the autonomous relations between plants and their environment that is more in line with modern ecological thought. Both Aristotle and Theophrastus made extensive observations on plant and animal migrations, biogeography, physiology, and their habits in what might be considered a modern analog of the ecological niche.[207] [208]

From Aristotle to Darwin the natural world was predominantly considered static and unchanged since its original creation. Prior to *The Origin of Species* there was little appreciation or understanding of the dynamic and reciprocal relations between organisms, their adaptations and their modifications to the environment.[200] [211] While Charles Darwin is most notable for his treatise on evolution,[212] he is also one of the founders of soil ecology.[213] In *The Origin of Species* Darwin also made note of the first ecological experiment that was published in 1816.[209] In the science leading up to Darwin the notion of evolving species was gaining popular support. This scientific paradigm changed the way that researchers approached the ecological sciences.[214]



The layout of the first ecological experiment, noted by Charles Darwin in *The Origin of Species*, was studied in a grass garden at Woburn Abbey in 1817. The experiment studied the performance of different mixtures of species planted in different kinds of soils.[209] [210]

Nowhere can one see more clearly illustrated what may be called the sensibility of such an organic complex,--expressed by the fact that whatever affects any species belonging to it, must speedily have its influence of some sort upon the whole assemblage. He will thus be made to see the impossibility of studying any form completely, out of relation to the other forms,--the necessity for taking a comprehensive survey of the whole as a condition to a satisfactory understanding of any part.

Stephen Forbes (1887)[215]

Ecology after the turn of 20th century

The first American ecology book was published in 1905 by Frederic Clements.[216] In his book, Clements forwarded the idea of plant communities as a superorganism. This publication launched a debate between ecological holism and individualism that lasted until the 1970s. The Clements superorganism concept proposed that ecosystems progress through regular and determined stages of seral development that are analogous to developmental stages of an organism whose parts function to maintain the integrity of the whole. The Clementsian paradigm was challenged by Henry Gleason.[217] According to Gleason, ecological communities develop from the unique and coincidental association of individual organisms. This perceptual shift placed the focus back onto the life histories of individual organisms and how this relates to the development of community associations.[218]

The Clementsian superorganism concept has not been completely rejected, but it was an overextended application of holism,[155] which remains a significant theme in contemporary ecological studies.[219] Holism was first introduced in 1926 by a polarizing historical figure, a South African General named Jan Christian Smuts. Smuts was inspired by Clement's superorganism theory when he developed and published on the unifying concept of holism, which runs in stark contrast to his racial views as the father of apartheid.[220] Around the same time, Charles Elton pioneered the concept of food chains in his classical book "Animal Ecology".[78] Elton[78] defined ecological relations using concepts of food-chains, food-cycles, food-size, and described numerical relations among different functional groups and their relative abundance. Elton's term 'food-cycle' was replaced by 'food-web' in a subsequent ecological text.[221] Elton's book broke conceptual ground by illustrating complex ecological relations through simpler food-web diagrams.[69]

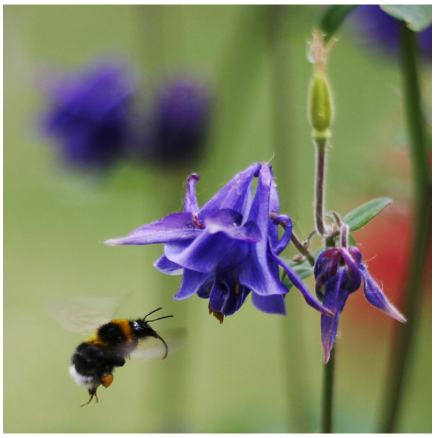
The number of authors publishing on the topic of ecology has grown considerably since the turn of 20th century.[222] The explosion of information available to the modern researcher of ecology makes it an impossible task for one individual to sift through the entire history. Hence, the identification of classics in the history of ecology is a difficult designation to make.[223]

Parallel development

Ecology has developers in many nations, including Russia's Vladimir Vernadsky and his founding of the biosphere concept in the 1920s[224] or Japan's Kinji Imanishi and his concepts of harmony in nature and habitat segregation in the 1950s.[225] The scientific recognition or importance of contributions to ecology from other cultures is hampered by language and translation barriers.[224] The history of ecology remains an active area of study, often published in the Journal of the History of Biology [226].

Ecosystem services and the biodiversity crisis

Increasing globalization of human activities and rapid movements of people as well as their goods and services suggest that mankind is now in an era of novel coevolution of ecological and socioeconomic systems at regional and global scales.[219] :642



A bumblebee pollinating a flower, one example of an ecosystem service

The ecosystems of planet Earth are coupled to human environments. Ecosystems regulate the global geophysical cycles of energy, climate, soil nutrients, and water that in turn support and grow natural capital (including the environmental, physiological, cognitive, cultural, and spiritual dimensions of life). Ultimately, every manufactured product in human environments comes from natural systems.[219] Ecosystems are considered common-pool resources because ecosystems do not exclude beneficiaries and they can be depleted or degraded.[227] For example, green space within communities provides common-pool health services. Research shows that people who are more engaged with regular access to natural areas have lower rates of diabetes, heart disease and psychological disorders.[228] These ecological health services are regularly depleted through urban development projects that do not factor in the common-pool value of ecosystems.[229] [230]

The ecological commons delivers a diverse supply of community services that sustains the well-being of human society.[231] [232] The Millennium Ecosystem Assessment, an international UN initiative involving more than 1,360 experts worldwide, identifies four main ecosystem service types having 30 sub-categories stemming from natural capital. The ecological commons includes provisioning (e.g., food, raw materials, medicine, water supplies), regulating (e.g., climate, water, soil retention, flood retention), cultural (e.g., science and education, artistic, spiritual), and supporting (e.g., soil formation, nutrient cycling, water cycling) services.[233]

Policy and human institutions should rarely assume that human enterprise is benign. A safer assumption holds that human enterprise almost always exacts an ecological toll - a debit taken from the ecological commons.[234] :95

Ecology is an economic science that uses many of the same terms and methods that are used in accounting.[235] Natural capital is the stock of materials or information stored in biodiversity that generates services that can enhance the welfare of communities.[236] Population losses are the more sensitive indicator of natural capital than are species extinction in the accounting of ecosystem services. The prospect for recovery in the economic crisis of nature is grim. Populations, such as local ponds and patches of forest are being cleared away and lost at rates that exceed species extinctions.[31]

While we are used to thinking of cities as geographically discrete places, most of the land "occupied" by their residents lies far beyond their borders. The total area of land required to sustain an urban region (its "ecological footprint") is typically at least an order of magnitude greater than that contained within municipal boundaries or the associated built-up area.[237] :121

The WWF 2008 living planet report and other researchers report that human civilization has exceeded the bio-regenerative capacity of the planet.[238] [239] This means that human consumption is extracting more natural resources than can be replenished by ecosystems around the world. In 1992, professor William Rees developed the concept of our ecological footprint. The ecological footprint is a way of accounting the level of impact that human

development is having on the Earth's ecosystems.[237] All indications are that the human enterprise is unsustainable as the ecological footprint of society is placing too much stress on the ecology of the planet.[239] The mainstream growth-based economic system adopted by governments worldwide does not include a price or markets for natural capital. This type of economic system places further ecological debt onto future generations.[240]

Human societies are increasingly being placed under stress as the ecological commons is diminished through an accounting system that has incorrectly assumed "... that nature is a fixed, indestructible capital asset."[241] :44 While nature is resilient and it does regenerate, there are limits to what can be extracted, but conventional monetary analyses are unable to detect the problem.[242] [243] Evidence of the limits in natural capital are found in the global assessments of biodiversity, which indicate that the current epoch, the Anthropocene[244] is a sixth mass extinction. Species loss is accelerating at 100–1000 times faster than average background rates in the fossil record.[245] [246] The ecology of the planet has been radically transformed by human society and development causing massive loss of ecosystem services that otherwise deliver and freely sustain equitable benefits to human society through the ecological commons. The ecology of the planet is further threatened by global warming, but investments in nature conservation can provide a regulatory feedback to store and regulate carbon and other greenhouse gases.[247] [248] The field of conservation biology involves ecologists that are researching the nature of the biodiversity threat and searching for solutions to sustain the planet's ecosystems for future generations.[249]

Many human-nature interactions occur indirectly due to the production and use of human-made (manufactured and synthesized) products, such as electronic appliances, furniture, plastics, airplanes, and automobiles. These products insulate humans from the natural environment, leading them to perceive less dependence on natural systems than is the case, but all manufactured products ultimately come from natural systems.[219] :640

> "Human activities are associated directly or indirectly with nearly every aspect of the current extinction spasm."[245] :11472

The current wave of threats, including massive extinction rates and concurrent loss of natural capital to the detriment of human society, is happening rapidly. This is called a biodiversity crisis, because 50% of the worlds species are predicted to go extinct within the next 50 years.[250] [251] The world's fisheries are facing dire challenges as the threat of global collapse appears imminent, with serious ramifications for the well-being of humanity.[252] Governments of the G8 met in 2007 and set forth 'The Economics of Ecosystems and Biodiversity' (TEEB) initiative [253]:

> In a global study we will initiate the process of analyzing the global economic benefit of biological diversity, the costs of the loss of biodiversity and the failure to take protective measures versus the costs of effective conservation.[254]

Ecologists are teaming up with economists to measure the wealth of ecosystems and to express their value as a way of finding solutions to the biodiversity crisis.[255] [256] [257] Some researchers have attempted to place a dollar figure on ecosystem services, such as the value that the Canadian boreal forest is contributing to global ecosystem services. If ecologically intact, the boreal forest has an estimated value of US$3.7 trillion. The boreal forest ecosystem is one of the planet's great atmospheric regulators and it stores more carbon than any other biome on the planet.[258] The annual value for ecological services of the Boreal Forest is estimated at US$93.2 billion, or 2.5 greater than the annual value of resource extraction. The economic value of 17 ecosystem services for the entire biosphere (calculated in 1997) has an estimated average value of US$33 trillion ($10^{12}$) per year.[236] These ecological economic values are not currently included in calculations of national income accounts, the GDP and they have no price attributes because they exist mostly outside of the global markets.[259] [260] The loss of natural capital continues to accelerate and goes undetected by mainstream monetary analysis.[261]

See also


Bachalpsee in the Swiss Alps; generally mountainous areas are less affected by human activity.

- Acoustic ecology
- Agroecology
- Aquatic ecosystems
- Biodiversity
- Biotope
- Biogeography
- Climate
- Conservation movement
- Earth science
- Ecoacoustics
- Ecohydrology
- Ecological economics
- Ecological Forecasting
- Ecology movement
- Ecology of contexts
- Ecosystem
- Ecosystem model
- Ecological psychology
- Ecological Relationships
- Ecosystem services
- Ecotope
- ELDIS, database ecological aspects of economical development.
- Environment
- Forest farming
- Forest gardening
- Habitat conservation
- Human ecology
- Industrial ecology
- Insect ecology
- Knowledge ecology
- Landscape ecology
- Landscape limnology
- Molecular ecology
- Natural capital
- Natural landscape
- Natural resource
- Natural resource management
- Nature
- Palaeoecology
- Social ecology
- Soil
- Sustainability
- Sustainable development

Lists

- Index of biology articles
- Glossary of ecology
- List of ecologists
- List of important publications in biology#Ecology
- Outline of biology

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External links

- stanford.edu/entries/ecology/ Ecology (Stanford Encyclopedia of Philosophy) [272]
- Science Aid: Ecology [273] High School (GCSE, Alevel) Ecology.
- Ecology Journals [274] List of scientific journals related to Ecology
- Ecology Dictionary - Explanation of Ecological Terms [275]
- [113] International Society for Behavioral Ecology

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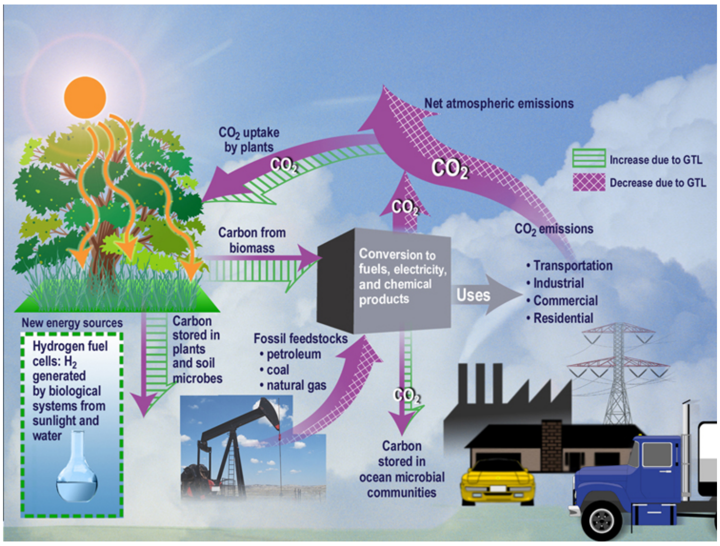
Systems ecology

Systems ecology is an interdisciplinary field of ecology, taking a holistic approach to the study of ecological systems, especially ecosystems. Systems ecology can be seen as an application of general systems theory to ecology. Central to the systems ecology approach is the idea that an ecosystem is a complex system exhibiting emergent properties. Systems ecology focuses on interactions and transactions within and between biological and ecological systems, and is especially concerned with the way the functioning of ecosystems can be influenced by human interventions. It uses and extends concepts from thermodynamics and develops other macroscopic descriptions of complex systems.



Ecological analysis of CO_2 in an ecosystem

Overview

Systems ecology seeks a holistic view of the interactions and transactions within and between biological and ecological systems. Systems ecologists realise that the function of any ecosystem can be influenced by human economics in fundamental ways. They have therefore taken an additional transdisciplinary step by including economics in the consideration of ecological-economic systems. In the words of R.L. Kitching:[1]

- *Systems ecology can be defined as the approach to the study of ecology of organisms using the techniques and philosophy of systems analysis: that is, the methods and tools developed, largely in engineering, for studying, characteriszing and making predictions about complex entities, that is, systems..*
- *In any study of an ecological system, an essential early procedure is to draw a diagram of the system of interest ... diagrams indicate the system's* ***boundaries*** *by a solid line. Within these boundaries, series of components are isolated which have been chosen to represent that portion of the world in which the systems analyst is interested ... If there are no connections across the systems' boundaries with the surrounding* ***systems environments****, the systems are described as* closed*. Ecological work, however, deals almost exclusively with* open *systems.*[2]

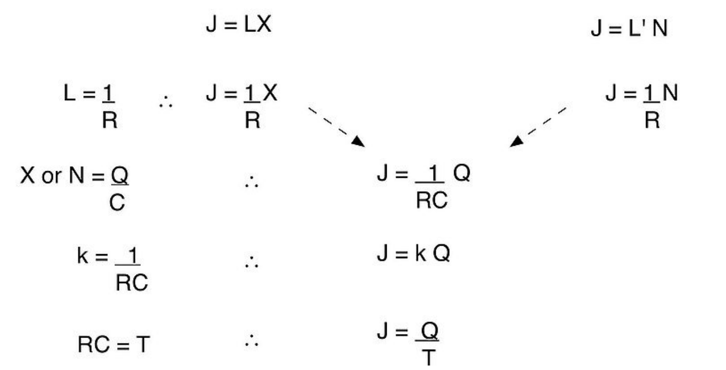
As a mode of scientific enquiry, a central feature of Systems Ecology is the general application of the principles of energetics to all systems at any scale. Perhaps the most notable proponent of this view was Howard T. Odum - sometimes considered the father of ecosystems ecology. In this approach the principles of energetics constitute ecosystem principles. Reasoning by formal analogy from one system to another enables the Systems Ecologist to see principles functioning in an analogous manner across system-scale boundaries. H.T. Odum commonly used the Energy Systems Language as a tool for making systems diagrams and flow charts.

The fourth of these principles, the principle of maximum power efficiency, takes central place in the analysis and synthesis of ecological systems. The fourth principle suggests that the most evolutionarily advantageous system function occurs when the environmental load matches the internal resistance of the system. The further the environmental load is from matching the internal resistance, the further the system is away from its sustainable steady state. Therefore the systems ecologist engages in a task of resistance and impedance matching in ecological engineering, just as the electronic engineer would do.

Summary of relationships in systems ecology

The image to the right is a summary of relationships between the storage quantity *Q*, the forces *X, N*, and the outflows *J*, resistance *R*, conductivity *L*, time constants *T*, and transfer coefficients *k* of ecosystem metabolism. The transfer coefficient "*k*", is also known as the *metabolic constant*.

> *"All these relationships are automatically implied by the energy circuit symbol* ". [3]



summary of relationships

Closely related fields

Deep Ecology

Deep Ecology is a school of philosophy pioneered by the Norwegian Philosopher, Gandhian scholar and environmental activist Arne Naess. Created in 1973 at an environmental conference in Budapest, it argues that the school of environmental management is anthropocentric, that the natural environment is not only "more complex than we imagine, it is more complex than we can imagine"[4] . Concerned with the development of an "ecological self", which views the human ego as a part of a living system, rather than apart from such systems, "Experiential Deep Ecology" of Joanna Macy, John Seed and others, seeks to transcend altruism with a deeper self-interest, based upon biospherical equality beyond human chauvinism.

Earth systems engineering and management

Earth systems engineering and management (ESEM) is a discipline used to analyze, design, engineer and manage complex environmental systems. It entails a wide range of subject areas including anthroplogy, engineering, environmental science, ethics and philosophy. At its core, ESEM looks to "rationally design and manage coupled human-natural systems in a highly integrated and ethical fashion"

Ecological economics

Ecological economics is a transdisciplinary field of academic research that addresses the dynamic and spatial interdependence between human economies and natural ecosystems. Ecological economics brings together and connects different disciplines, within the natural and social sciences but especially between these broad areas. As the name suggests, the field is made up of researchers with a background in economics and ecology. An important motivation for the emergence of ecological economics has been criticism on the assumptions and approaches of traditional (mainstream) environmental and resource economics.

Ecological energetics

Ecological energetics is the quantitative study of the flow of energy through ecological systems. It aims to uncover the principles which describe the propensity of such energy flows through the trophic, or 'energy availing' levels of ecological networks. In systems ecology the principles of ecosystem energy flows or "ecosystem laws" (i.e. principles of ecological energetics) are considered formally analogous to the principles of energetics.

Ecological humanities

Ecological humanities aims to bridge the divides between the sciences and the humanities, and between Western, Eastern and Indigenous ways of knowing nature. Like ecocentric political theory, the ecological humanities are characterised by a connectivity ontology and a commitment to two fundamental axioms relating to the need to submit to ecological laws and to see humanity as part of a larger living system.

Ecosystem ecology

A riparian forest in the White Mountains, New Hampshire (USA)

Ecosystem ecology is the integrated study of biotic and abiotic components of ecosystems and their interactions within an ecosystem framework. This science examines how ecosystems work and relates this to their components such as chemicals, bedrock, soil, plants, and animals. Ecosystem ecology examines physical and biological structure and examines how these ecosystem characteristics interact.

The relationship between systems ecology and ecosystem ecology is complex. Much of systems ecology can be considered a subset of ecosystem ecology. Ecosystem ecology also utilizes methods that have little to do with the holistic approach of systems ecology. However, systems ecology more actively considers external influences such as economics that usually fall outside the bounds of ecosystem ecology. Whereas ecosystem ecology can be defined as the scientific study of ecosystems, systems ecology is more of a particular approach to the study of ecological systems and phenomena that interact with these systems.

Industrial ecology

Industrial ecology is the study of industrial processes as linear (open loop) systems, in which resource and capital investments move through the system to become waste, to a closed loop system where wastes become inputs for new processes.

See also

- Agroecology
- Ecological literacy
- Economics and energy
- Emergy
- Energetics
- Energy Systems Language
- Holism in science
- Holistic management
- Landscape ecology
- Antireductionism

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External links

Organisations

- Systems Ecology Department [5] at the Stockholm University.
- Systems Ecology Department [6] at the University of Amsterdam.
- Systems ecology Lab [7] at SUNY-ESF.
- Systems Ecology program [8] at the University of Florida
- Terrestrial Systems Ecology [9] of ETH Zurich.

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[9] http://www.sysecol.ethz.ch/

Ecological genetics

Ecological genetics is the study of genetics in the context of the interactions among organisms and between the organisms and their environment. While molecular genetics studies the structure and function of genes at a molecular level, ecological genetics (and the related field of population genetics) studies phenotypic evolution in natural populations of organisms. Research in this field is of traits of ecological significance — that is, traits related to fitness, which affect an organism's survival and reproduction (e.g., flowering time, drought tolerance, sex ratio).

Studies are often done on insects and other organisms that have short generation times, and thus evolve at high rates.

History

Although work on natural populations had been done previously, it is acknowledged that the field was founded by the English biologist E.B. Ford (1901-1988) in the early 20th century. Ford was taught genetics at Oxford University by Julian Huxley, and started research on the genetics of natural populations in 1924. *Ecological Genetics* is the title of his 1964 'magnum opus' on the subject (4th ed 1975). Other notable ecological geneticists would include Theodosius Dobzhansky who worked on chromosome polymorphism in fruit flies. As a young researcher in Russia, Dobzhansky had been influenced by Sergei Chetverikov, who also deserves to be remembered as a founder of genetics in the field, though his significance was not appreciated until much later.

Philip Sheppard, Cyril Clarke, Bernard Kettlewell and A.J. Cain were all strongly influenced by Ford; their careers date from the post WWII era. Collectively, their work on lepidopterans, and on human blood groups, established the field, and threw light on selection in natural populations where its role had been once doubted.

Work of this kind needs long-term funding, as well as grounding in both ecology and genetics. These are both difficult requirements. Research projects can last longer than a researcher's career; for instance, research into

mimicry started 150 years ago, and is still going strongly. Funding of this type of research is still rather erratic, but at least the value of working with natural populations in the field cannot now be doubted.

See also

- antibiotic resistance
- peppered moth, *Biston betularia*,
- pesticide resistance
- polymorphism (biology)
- scarlet tiger moth, *Calimorpha dominula*,

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- Conner, J.K. and Hartl, D. L. "A Primer of Ecological Genetics". Sinauer Associates, Inc.; Sunderland, Mass. (2004) Provides basic and intermediate level processes and methods.

Molecular evolution

Molecular evolution is the process of evolution at the scale of DNA, RNA, and proteins. Molecular evolution emerged as a scientific field in the 1960s as researchers from molecular biology, evolutionary biology and population genetics sought to understand recent discoveries on the structure and function of nucleic acids and protein. Some of the key topics that spurred development of the field have been the evolution of enzyme function, the use of nucleic acid divergence as a "molecular clock" to study species divergence, and the origin of non-functional or junk DNA. Recent advances in genomics, including whole-genome sequencing, high-throughput protein characterization, and bioinformatics have led to a dramatic increase in studies on the topic. In the 2000s, some of the active topics have been the role of gene duplication in the emergence of novel gene function, the extent of adaptive molecular evolution versus neutral drift, and the identification of molecular changes responsible for various human characteristics especially those pertaining to infection, disease, and cognition.

Principles of molecular evolution

Mutations

Mutations are permanent, transmissible changes to the genetic material (usually DNA or RNA) of a cell. Mutations can be caused by copying errors in the genetic material during cell division and by exposure to radiation, chemicals, or viruses, or can occur deliberately under cellular control during the processes such as meiosis or hypermutation. Mutations are considered the driving force of evolution, where less favorable (or *deleterious*) mutations are removed from the gene pool by natural selection, while more favorable (or *beneficial*) ones tend to accumulate. Neutral mutations do not affect the organism's chances of survival in its natural environment and can accumulate over time, which might result in what is known as punctuated equilibrium; the modern interpretation of classic evolutionary theory.

Causes of change in allele frequency

There are three known processes that affect the survival of a characteristic; or, more specifically, the frequency of an allele (variant of a gene):

- Genetic drift describes changes in gene frequency that cannot be ascribed to selective pressures, but are due instead to events that are unrelated to inherited traits. This is especially important in small mating populations, which simply cannot have enough offspring to maintain the same gene distribution as the parental generation.
- Gene flow or Migration: or gene admixture is the only one of the agents that makes populations closer genetically while building larger gene pools.
- Selection, in particular natural selection produced by differential mortality and fertility. Differential mortality is the survival rate of individuals before their reproductive age. If they survive, they are then selected further by differential fertility – that is, their total genetic contribution to the next generation. In this way, the alleles that these surviving individuals contribute to the gene pool will increase the frequency of those alleles. Sexual selection, the attraction between mates that results from two genes, one for a feature and the other determining a preference for that feature, is also very important.

Molecular study of phylogeny

Molecular systematics is a product of the traditional field of systematics and molecular genetics. It is the process of using data on the molecular constitution of biological organisms' DNA, RNA, or both, in order to resolve questions in systematics, i.e. about their correct scientific classification or taxonomy from the point of view of evolutionary biology.

Molecular systematics has been made possible by the availability of techniques for DNA sequencing, which allow the determination of the exact sequence of nucleotides or *bases* in either DNA or RNA. At present it is still a long and expensive process to sequence the entire genome of an organism, and this has been done for only a few species. However, it is quite feasible to determine the sequence of a defined area of a particular chromosome. Typical molecular systematic analyses require the sequencing of around 1000 base pairs.

The driving forces of evolution

Depending on the relative importance assigned to the various forces of evolution, three perspectives provide evolutionary explanations for molecular evolution.[1]

While recognizing the importance of random drift for silent mutations,[2] **selectionists hypotheses** argue that balancing and positive selection are the driving forces of molecular evolution. Those hypotheses are often based on the broader view called panselectionism, the idea that selection is the only force strong enough to explain evolution, relaying random drift and mutations to minor roles.[1]

Neutralists hypotheses emphasize the importance of mutation, purifying selection and random genetic drift.[3] The introduction of the neutral theory by Kimura,[4] quickly followed by King and Jukes' own findings,[5] lead to a fierce debate about the relevance of neodarwinism at the molecular level. The Neutral theory of molecular evolution states that most mutations are deleterious and quickly removed by natural selection, but of the remaining ones, the vast majority are neutral with respect to fitness while the amount of advantageous mutations is vanishingly small. The fate of neutral mutations are governed by genetic drift, and contribute to both nucleotide polymorphism and fixed differences between species. [6] [7] [8]

Mutationists hypotheses emphasize random drift and biases in mutation patterns.[9] Sueoka was the first to propose a modern mutationist view. He proposed that the variation in GC content was not the result of positive selection, but a consequence of the GC mutational pressure.[10]

Related fields

An important area within the study of molecular evolution is the use of molecular data to determine the correct biological classification of organisms. This is called molecular systematics or molecular phylogenetics.

Tools and concepts developed in the study of molecular evolution are now commonly used for comparative genomics and molecular genetics, while the influx of new data from these fields has been spurring advancement in molecular evolution.

Key researchers in molecular evolution

Some researchers who have made key contributions to the development of the field:

- Motoo Kimura — Neutral theory
- Masatoshi Nei — Adaptive evolution
- Walter M. Fitch — Phylogenetic reconstruction
- Walter Gilbert — RNA world
- Joe Felsenstein — Phylogenetic methods
- Susumu Ohno — Gene duplication
- John H. Gillespie — Mathematics of adaptation

Journals and societies

Journals dedicated to molecular evolution include *Molecular Biology and Evolution*, *Journal of Molecular Evolution*, and *Molecular Phylogenetics and Evolution*. Research in molecular evolution is also published in journals of genetics, molecular biology, genomics, systematics, or evolutionary biology. The Society for Molecular Biology and Evolution [11] publishes the journal "Molecular Biology and Evolution" and holds an annual international meeting.

See also

- History of molecular evolution
- Chemical evolution
- Evolution
- Genetic drift
- *E. coli* long-term evolution experiment
- Evolutionary physiology
- Genomic organization
- Horizontal gene transfer
- Human evolution
- Evolution of dietary antioxidants
- Molecular clock
- Comparative phylogenetics
- Neutral theory of molecular evolution
- Nucleotide diversity
- Parsimony
- Population genetics
- Selection

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[7] The nearly neutral theory expanded the neutralist perspective, suggesting that several mutations are nearly neutral, which means both random drift and natural selection is relevant to their dynamics.
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[11] http://www.smbe.org

Evolutionary history of life

The evolutionary history of life on Earth traces the processes by which living and fossil organisms evolved. It stretches from the origin of life on Earth, thought to be over 3500 [1] million years ago, to the present day. The similarities between all present day organisms indicate the presence of a common ancestor from which all known species have diverged through the process of evolution.[2]

Microbial mats of coexisting bacteria and archaea were the dominant form of life in the early Archean and many of the major steps in early evolution are thought to have taken place within them.[3] The evolution of oxygenic photosynthesis, around 3500 [1] million years ago, eventually led to the oxygenation of the atmosphere, beginning around 2400 [4] million years ago.[5] While eukaryotic cells may have been present earlier, their evolution accelerated when they began to use oxygen in their metabolism. The earliest evidence of complex eukaryotes with organelles, dates from 1850.0 [6] million years ago. Later, around 1700 [7] million years ago, multicellular organisms began to appear, with differentiated cells performing specialised functions.[8]

The earliest land plants date back to around 450.0 [9] million years ago,[10] though evidence suggests that algal scum formed on the land as early as 1200 [11] million years ago. Land plants were so successful that they are thought to have contributed to the late Devonian extinction event.[12] Invertebrate animals appear during the Vendian period,[13] while vertebrates originated about 525 [14] million years ago during the Cambrian explosion.[15]

During the Permian period, synapsids, including the ancestors of mammals, dominated the land,[16] but the Permian–Triassic extinction event 251.0 [17] million years ago came close to wiping out all complex life.[18] During the recovery from this catastrophe, archosaurs became the most abundant land vertebrates, displacing therapsids in the mid-Triassic.[19] One archosaur group, the dinosaurs, dominated the Jurassic and Cretaceous periods,[20] while the ancestors of mammals survived only as small insectivores.[21] After the Cretaceous–Tertiary extinction event 65 [22] million years ago killed off the non-avian dinosaurs[23] mammals increased rapidly in size and diversity.[24] Such mass extinctions may have accelerated evolution by providing opportunities for new groups of organisms to diversify.[25]

Fossil evidence indicates that flowering plants appeared and rapidly diversified in the Early Cretaceous, between 130 [26] million years ago and 90 [27] million years ago, probably helped by coevolution with pollinating insects. Flowering plants and marine phytoplankton are still the dominant producers of organic matter. Social insects appeared around the same time as flowering plants. Although they occupy only small parts of the insect "family tree", they now form over half the total mass of insects. Humans evolved from a lineage of upright-walking apes whose earliest fossils date from over 6 [28] million years ago. Although early members of this lineage had chimp-sized brains, there are signs of a steady increase in brain size after about 3 [29] million years ago.

Earliest history of Earth

History of Earth and its life

Hadean

Archean

Protero
-zoic

Phanero
-zoic

Eo

Paleo

Meso

Neo

Paleo

Meso

Neo

Paleo

Meso

Ceno

Scale:

Millions of years

The oldest meteorite fragments found on Earth are about 4540 [30] million years old, and this has convinced scientists that the whole Solar system, including Earth, formed around that time.[31] About 40 million years later a planetoid struck the Earth, throwing into orbit the material that formed the Moon.[32]

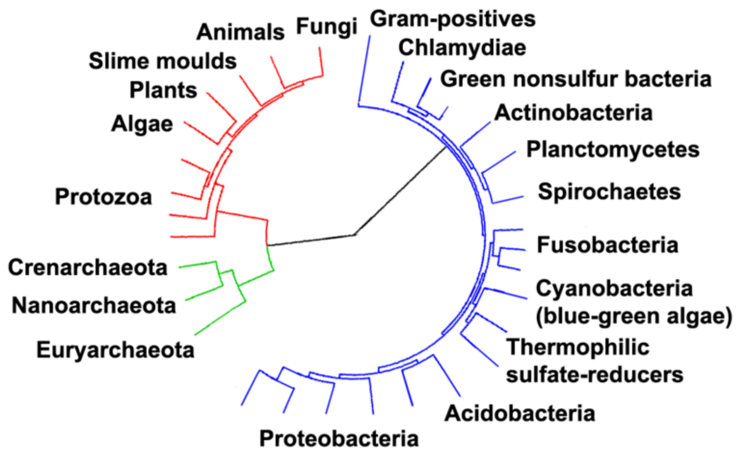
Until recently the oldest rocks found on Earth were about 3800 [33] million years old,[31] and this led scientists to believe for decades that Earth's surface was molten until then. Hence they named this part of Earth's history the Hadean eon, whose name means "hellish".[34] However analysis of zircons formed 4400 to 4000 [35] million years ago indicates that Earth's crust solidified about 100 million years after the planet's formation and that Earth quickly acquired oceans and an atmosphere, which may have been capable of supporting life.[36]

Evidence from the Moon indicates that from 4000 to 3800 [37] million years ago it suffered a Late Heavy Bombardment by debris that was left over from the formation of the Solar system, and Earth, having stronger gravity, should have experienced an even heavier bombardment.[34] [38] While there is no direct evidence of conditions on Earth 4000 to 3800 [37] million years ago, there is no reason to think that the Earth was not also affected by this late heavy bombardment.[39] This event may well have stripped away any previous atmosphere and oceans; in this case gases and water from comet impacts may have contributed to their replacement, although volcanic outgassing on Earth would have contributed at least half.[40]

Earliest evidence for life on Earth

The earliest identified organisms were minute and relatively featureless, so their fossils look like small rods, which are very difficult to tell apart from structures which form through physical processes. The oldest undisputed evidence of life on Earth, interpreted as fossilized bacteria, dates to 3000 [41] million years ago.[42] Other finds in rocks dated to about 3500 [1] million years ago have been interpreted as bacteria,[43] and geochemical evidence seemed to show the presence of life 3800 [33] million years ago.[44] However these analyses were closely scrutinized, and non-biological processes were found which could produce all of the "signatures of life" that had been reported.[45] [46] While this does not prove that the structures found had a non-biological origin, they cannot be taken as clear evidence for the presence of life. Currently, the oldest unchallenged evidence for life is geochemical signatures from rocks deposited 3400 [47] million years ago,[42] [48] although there has been little time for these recent reports (2006) to be examined by critics.

Origins of life on Earth



Evolutionary tree showing the divergence of modern species from their common ancestor in the center.Ciccarelli, F.D., Doerks, T., von Mering, C., Creevey, C.J., et al (2006). "Toward automatic reconstruction of a highly resolved tree of life". Science 311 (5765): 1283–7. doi:10.1126/science.1123061. PMID 16513982. The three domains are colored, with bacteria blue, archaea green, and eukaryotes red.

Biochemists reason that all living organisms on Earth must share a single last universal ancestor, because it would be virtually impossible that two or more separate lineages could have independently developed the many complex biochemical mechanisms shared by all living organisms.[49] [50] However the earliest organisms for which fossil evidence is available are bacteria, which are far too complex to have arisen directly from non-living materials.[51] The lack of fossil or geochemical evidence for earlier types of organism has left plenty of scope for hypotheses, which fall into two main groups: that life arose spontaneously on Earth, and that it was "seeded" from elsewhere in the universe.[52]

Life "seeded" from elsewhere

The idea that life Earth was "seeded" from elsewhere in the universe dates back at least to the fifth century BC.[53] In the twentieth century it was proposed by the physical chemist Svante Arrhenius,[54] by the astronomers Fred Hoyle and Chandra Wickramasinghe,[55] and by molecular biologist Francis Crick and chemist Leslie Orgel.[56] There are three main versions of the "seeded from elsewhere" hypothesis: from elsewhere in our Solar system via fragments knocked into space by a large meteor impact, in which case the only credible source is Mars;[57] by alien visitors, possibly as a result of accidental contamination by micro-organisms that they brought with them;[56] and from outside the Solar system but by natural means.[54] [57] Experiments suggest that some micro-organisms can survive the shock of being catapulted into space and some can survive exposure to radiation for several days, but there is no proof that they can survive in space for much longer periods.[57] Scientists are divided over the likelihood of life arising independently on Mars,[58] or on other planets in our galaxy.[57]

Independent emergence on Earth

Life on earth is based on carbon and water. Carbon provides stable frameworks for complex chemicals and can be easily extracted from the environment, especially from carbon dioxide. The only other element with similar chemical properties, silicon, forms much less stable structures and, because most of its compounds are solids, would be more difficult for organisms to extract. Water is an excellent solvent and has two other useful properties: the fact that ice floats enables aquatic organisms to survive beneath it in winter; and its molecules have electrically negative and positive ends, which enables it to form a wider range of compounds than other solvents can. Other good solvents, such as ammonia, are liquid only at such low temperatures that chemical reactions may be too slow to sustain life, and lack water's other advantages.[59] Organisms based on alternative biochemistry may however be possible on other planets.[60]

Research on how life might have emerged unaided from non-living chemicals focuses on three possible starting points: self-replication, an organism's ability to produce offspring that are very similar to itself; metabolism, its

ability to feed and repair itself; and external cell membranes, which allow food to enter and waste products to leave, but exclude unwanted substances.[61] Research on abiogenesis still has a long way to go, since theoretical and empirical approaches are only beginning to make contact with each other.[62] [63]

Replication first: RNA world

The replicator in virtually all known life is deoxyribonucleic acid. DNA's structure and replication systems are far more complex than those of the original replicator.[51]

Even the simplest members of the three modern domains of life use DNA to record their "recipes" and a complex array of RNA and protein molecules to "read" these instructions and use them for growth, maintenance and self-replication. This system is far too complex to have emerged directly from non-living materials.[51] The discovery that some RNA molecules can catalyze both their own replication and the construction of proteins led to the hypothesis of earlier life-forms based entirely on RNA.[64] These ribozymes could have formed an RNA world in which there were individuals but no species, as mutations and horizontal gene transfers would have meant that the offspring in each generation were quite likely to have different genomes from those that their parents started with.[65] RNA would later have been replaced by DNA, which is more stable and therefore can build longer genomes, expanding the range of capabilities a single organism can have.[65] [66] [67] Ribozymes remain as the main components of ribosomes, modern cells' "protein factories".[68]

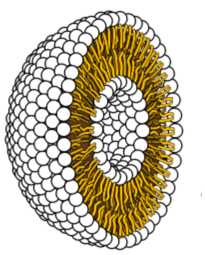
Although short self-replicating RNA molecules have been artificially produced in laboratories,[69] doubts have been raised about where natural non-biological synthesis of RNA is possible.[70] The earliest "ribozymes" may have been formed of simpler nucleic acids such as PNA, TNA or GNA, which would have been replaced later by RNA.[71] [72]

In 2003 it was proposed that porous metal sulfide precipitates would assist RNA synthesis at about 100 °C (212 °F) and ocean-bottom pressures near hydrothermal vents. In this hypothesis lipid membranes would be the last major cell components to appear and until then the proto-cells would be confined to the pores.[73]

Metabolism first: Iron-sulfur world

A series of experiments starting in 1997 showed that early stages in the formation of proteins from inorganic materials including carbon monoxide and hydrogen sulfide could be achieved by using iron sulfide and nickel sulfide as catalysts. Most of the steps required temperatures of about 100 °C (212 °F) and moderate pressures, although one stage required 250 °C (482 °F) and a pressure equivalent to that found under 7 kilometres (4.3 mi) of rock. Hence it was suggested that self-sustaining synthesis of proteins could have occurred near hydrothermal vents.[74]

Membranes first: Lipid world



= water-attracting heads of lipid molecules

= water-repellent tails

Cross-section through a liposome.

It has been suggested that double-walled "bubbles" of lipids like those that form the external membranes of cells may have been an essential first step.[75] Experiments that simulated the conditions of the early Earth have reported the formation of lipids, and these can spontaneously form liposomes, double-walled "bubbles", and then reproduce themselves. Although they are not intrinsically information-carriers as nucleic acids are, they would be subject to

natural selection for longevity and reproduction. Nucleic acids such as RNA might then have formed more easily within the liposomes than they would have outside.[76]

The clay theory

RNA is complex and there are doubts about whether it can be produced non-biologically in the wild.[70] Some clays, notably montmorillonite, have properties that make them plausible accelerators for the emergence of an RNA world: they grow by self-replication of their crystalline pattern; they are subject to an analog of natural selection, as the clay "species" that grows fastest in a particular environment rapidly becomes dominant; and they can catalyze the formation of RNA molecules.[77] Although this idea has not become the scientific consensus, it still has active supporters.[78]

Research in 2003 reported that montmorillonite could also accelerate the conversion of fatty acids into "bubbles", and that the "bubbles" could encapsulate RNA attached to the clay. These "bubbles" can then grow by absorbing additional lipids and then divide. The formation of the earliest cells may have been aided by similar processes.[79]

A similar hypothesis presents self-replicating iron-rich clays as the progenitors of nucleotides, lipids and amino acids.[80]

Environmental and evolutionary impact of microbial mats

Microbial mats are multi-layered, multi-species colonies of bacteria and other organisms that are generally only a few millimeters thick, but still contain a wide range of chemical environments, each of which favors a different set of micro-organisms.[81] To some extent each mat forms its own food chain, as the by-products of each group of micro-organisms generally serve as "food" for adjacent groups.[82]

Modern stromatolites in Shark Bay, Western Australia.

Stromatolites are stubby pillars built as microbes in mats slowly migrate upwards to avoid being smothered by sediment deposited on them by water.[81] There has been vigorous debate about the validity of alleged fossils from before 3000 [41] million years ago,[83] with critics arguing that so-called stromatolites could have been formed by non-biological processes.[45] In 2006 another find of stromatolites was reported from the same part of Australia as previous ones, in rocks dated to 3500 [1] million years ago.[84]

In modern underwater mats the top layer often consists of photosynthesizing cyanobacteria which create an oxygen-rich environment, while the bottom layer is oxygen-free and often dominated by hydrogen sulfide emitted by the organisms living there.[82] It is estimated that the appearance of oxygenic photosynthesis by bacteria in mats increased biological productivity by a factor of between 100 and 1,000. The reducing agent used by oxygenic photosynthesis is water, which is much more plentiful than the geologically-produced reducing agents required by the earlier non-oxygenic photosynthesis.[85] From this point onwards life itself produced significantly more of the resources it needed than did geochemical processes.[86] Oxygen is toxic to organisms that are not adapted to it, but greatly increases the metabolic efficiency of oxygen-adapted organisms.[87] [88]

Oxygen became a significant component of Earth's atmosphere about 2400 [4] million years ago.[89] Although eukaryotes may have been present much earlier,[90] [91] the oxygenation of the atmosphere was a prerequisite for the evolution of the most complex eukaryotic cells, from which all multicellular organisms are built.[92] The boundary between oxygen-rich and oxygen-free layers in microbial mats would have moved upwards when photosynthesis shut down overnight, and then downwards as it resumed on the next day. This would have created selection pressure for organisms in this intermediate zone to acquire the ability to tolerate and then to use oxygen, possibly via

endosymbiosis, where one organism lives inside another and both of them benefit from their association.[3]

Cyanobacteria have the most complete biochemical "toolkits" of all the mat-forming organisms. Hence they are the most self-sufficient of the mat organisms and were well-adapted to strike out on their own both as floating mats and as the first of the phytoplankton, providing the basis of most marine food chains.[3]

Diversification of eukaryotes

- Eukaryotes
  - Bikonta
    - Apusozoa
    - Archaeplastida (Land plants, green algae, red algae, and glaucophytes)
    - Chromalveolata
    - Rhizaria
    - Excavata
  - Unikonta
    - Amoebozoa
    - Opisthokonta
      - Metazoa (Animals)
      - Choanozoa
      - Eumycota (Fungi)

One possible family tree of eukaryotes[93] [94]

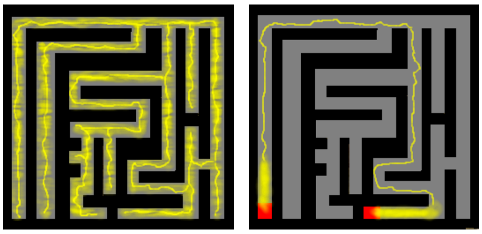
Eukaryotes may have been present long before the oxygenation of the atmosphere,[90] but most modern eukaryotes require oxygen, which their mitochondria use to fuel the production of ATP, the internal energy supply of all known cells.[92] In the 1970s it was proposed and, after much debate, widely accepted that eukaryotes emerged as a result of a sequence of endosymbioses between "procaryotes". For example: a predatory micro-organism invaded a large procaryote, probably an archaean, but the attack was neutralized, and the attacker took up residence and evolved into the first of the mitochondria; one of these chimeras later tried to swallow a photosynthesizing cyanobacterium, but the victim survived inside the attacker and the new combination became the ancestor of plants; and so on. After each endosymbiosis began, the partners would have eliminated unproductive duplication of genetic functions by re-arranging their genomes, a process which sometimes involved transfer of genes between them.[95] [96] [97] Another hypothesis proposes that mitochondria were originally sulfur- or hydrogen-metabolising endosymbionts, and became oxygen-consumers later.[98] On the other hand mitochondria might have been part of eukaryotes' original equipment.[99]

There is a debate about when eukaryotes first appeared: the presence of steranes in Australian shales may indicate that eukaryotes were present 2700 [100] million years ago;[91] however an analysis in 2008 concluded that these chemicals infiltrated the rocks less than 2200 [101] million years ago and prove nothing about the origins of eukaryotes.[102] Fossils of the alga *Grypania* have been reported in 1850.0 [6] million-year-old rocks (originally dated to 2100 [103] million years ago but later revised[104]), and indicates that eukaryotes with organelles had already evolved.[105] A diverse collection of fossil algae were found in rocks dated between 1500 [106] million years ago and 1400 [107] million years ago.[108] The earliest known fossils of fungi date from 1430 [109] million years ago.[110]

Multicellular organisms and sexual reproduction

Multicellularity

The simplest definitions of "multicellular", for example "having multiple cells", could include colonial cyanobacteria like Nostoc. Even a professional biologist's definition such as "having the same genome but different types of cell" would still include some genera of the green alga Volvox, which have cells that specialize in reproduction.[112] Multicellularity evolved independently in organisms as diverse as sponges and other animals, fungi, plants, brown algae, cyanobacteria, slime moulds and myxobacteria.[104][113] For the sake of brevity this article focuses on the organisms that show the greatest specialization of cells and variety of cell types, although this approach to the evolution of complexity could be regarded as "rather anthropocentric".[114]



A slime mold solves a maze. The mold (yellow) explored and filled the maze (left). When the researchers placed sugar (red) at two separate points, the mold concentrated most of its mass there and left only the most efficient connection between the two points (right).[111]

The initial advantages of multicellularity may have included: increased resistance to predators, many of which attacked by engulfing; the ability to resist currents by attaching to a firm surface; the ability to reach upwards to filter-feed or to obtain sunlight for photosynthesis;[115] the ability to create an internal environment that gives protection against the external one;[114] and even the opportunity for a group of cells to behave "intelligently" by sharing information.[111] These features would also have provided opportunities for other organisms to diversify, by creating more varied environments than flat microbial mats could.[115]

Multicellularity with differentiated cells is beneficial to the organism as a whole but disadvantageous from the point of view of individual cells, most of which lose the opportunity to reproduce themselves. In an asexual multicellular organism, rogue cells which retain the ability to reproduce may take over and reduce the organism to a mass of undifferentiated cells. Sexual reproduction eliminates such rogue cells from the next generation and therefore appears to be a prerequisite for complex multicellularity.[115]

The available evidence indicates that eukaryotes evolved much earlier but remained inconspicuous until a rapid diversification around 1000 [116] million years ago. The only respect in which eukaryotes clearly surpass bacteria and archaea is their capacity for variety of forms, and sexual reproduction enabled eukaryotes to exploit that advantage by producing organisms with multiple cells that differed in form and function.[115]

Evolution of sexual reproduction

The defining characteristic of sexual reproduction is recombination, in which each of the offspring receives 50% of its genetic inheritance from each of the parents.[117] Bacteria also exchange DNA by bacterial conjugation, the benefits of which include resistance to antibiotics and other toxins, and the ability to utilize new metabolites.[118] However conjugation is not a means of reproduction, and is not limited to members of the same species – there are cases where bacteria transfer DNA to plants and animals.[119]

The disadvantages of sexual reproduction are well-known: the genetic reshuffle of recombination may break up favorable combinations of genes; and since males do not directly increase the number of offspring in the next generation, an asexual population can out-breed and displace in as little as 50 generations a sexual population that is equal in every other respect.[117] Nevertheless the great majority of animals, plants, fungi and protists reproduce sexually. There is strong evidence that sexual reproduction arose early in the history of eukaryotes and that the genes controlling it have changed very little since then.[120] How sexual reproduction evolved and survived is an unsolved puzzle.[121]

The Red Queen Hypothesis suggests that sexual reproduction provides protection against parasites, because it is easier for parasites to evolve means of overcoming the defenses of genetically identical clones than those of sexual species that present moving targets, and there is some experimental evidence for this. However there is still doubt about whether it would explain the survival of sexual species if multiple similar clone species were present, as one of the clones may survive the attacks of parasites for long enough to out-breed the sexual species.[117]

The Mutation Deterministic Hypothesis assumes that each organism has more than one harmful mutation and the combined effects of these mutations are more harmful than the sum of the harm done by each individual mutation. If so, sexual recombination of genes will reduce the harm done that bad mutations do to offspring and at the same time eliminate some bad mutations from the gene pool by isolating them in individuals that perish quickly because they have an above-average number of bad mutations. However the evidence suggests that the MDH's assumptions are shaky, because many species have on average less than one harmful mutation per individual and no species that has been investigated shows evidence of synergy between harmful mutations.[117]

The random nature of recombination causes the relative abundance of alternative traits to vary from one generation to another. This genetic drift is insufficient on its own to make sexual reproduction advantageous, but a combination of genetic drift and natural selection may be sufficient. When chance produces combinations of good traits, natural selection gives a large advantage to lineages in which these traits become genetically linked. On the other hand the benefits of good traits are neutralized if they appear along with bad traits. Sexual recombination gives good traits the opportunities to become linked with other good traits, and mathematical models suggest this may be more than enough to offset the disadvantages of sexual reproduction.[121] Other combinations of hypotheses that are inadequate on their own are also being examined.[117]

Fossil evidence for multicellularity and sexual reproduction

Horodyskia may have been an early metazoan,[104] or a colonial foraminiferan[122]

The earliest known fossil organism that is clearly multicellular, *Qingshania*,[123] dated to 1700 [7] million years ago, appears to consist of virtually identical cells. A red alga called *Bangiomorpha*, dated at 1200 [11] million years ago, is the earliest known organism which has differentiated, specialized cells, and is also the oldest known sexually-reproducing organism.[115] The 1430 [109] million-year-old fossils interpreted as fungi appear to have been multicellular with differentiated cells.[110] The "string of beads" organism *Horodyskia*, found in rocks dated from 1500 [106] million years ago to 900.0 [124] million years ago, may have been an early metazoan;[104] however it has also been interpreted as a colonial foraminiferan.[122]

Emergence of animals

Bilaterians

Deuterostomes (chordates, hemichordates, echinoderms)

Protostomes

Ecdysozoa (anthropods, nematodes, tardigrades, etc.)

Lophotrochozoa (molluscs, annelids, brachiopods, etc.)

Acoelomorpha

Cnidaria (jellyfish, sea anemones, hydras)

Ctenophora (comb jellies)

Placozoa

Porifera (sponges): Calcarea

Porifera: Hexactinellida & Demospongiae

Choanoflagellata

Mesomycetozoea

A family tree of the animals.[125]

Animals are multicellular eukaryotes,[126] and are distinguished from plants, algae, and fungi by lacking cell walls.[127] All animals are motile,[128] if only at certain life stages. All animals except sponges have bodies differentiated into separate tissues, including muscles, which move parts of the animal by contracting, and nerve tissue, which transmits and processes signals.[129]

The earliest widely-accepted animal fossils are rather modern-looking cnidarians (the group that includes jellyfish, sea anemones and hydras), possibly from around 580 [130] million years ago, although fossils from the Doushantuo Formation can only be dated approximately. Their presence implies that the cnidarian and bilaterian lineages had already diverged.[131]

The Ediacara biota, which flourished for the last 40 million years before the start of the Cambrian,[132] were the first animals more than a very few centimeters long. Many were flat and had a "quilted" appearance, and seemed so strange that there was a proposal to classify them as a separate kingdom, Vendozoa.[133] Others, however, been interpreted as early molluscs (*Kimberella*[134] [135]), echinoderms (*Arkarua*[136]), and arthropods (*Spriggina*,[137] *Parvancorina*[138]). There is still debate about the classification of these specimens, mainly because the diagnostic features which allow taxonomists to classify more recent organisms, such as similarities to living organisms, are generally absent in the Ediacarans. However there seems little doubt that *Kimberella* was at least a triploblastic bilaterian animal, in other words significantly more complex than cnidarians.[139]

The small shelly fauna are a very mixed collection of fossils found between the Late Ediacaran and Mid Cambrian periods. The earliest, *Cloudina*, shows signs of successful defense against predation and may indicate the start of an evolutionary arms race. Some tiny Early Cambrian shells almost certainly belonged to molluscs, while the owners of some "armor plates", *Halkieria* and *Microdictyon*, were eventually identified when more complete specimens were

found in Cambrian lagerstätten that preserved soft-bodied animals.[140]

Opabinia made the largest single contribution to modern interest in the Cambrian explosion.[141]

In the 1970s there was already a debate about whether the emergence of the modern phyla was "explosive" or gradual but hidden by the shortage of Pre-Cambrian animal fossils.[140] A re-analysis of fossils from the Burgess Shale lagerstätte increased interest in the issue when it revealed animals, such as *Opabinia*, which did not fit into any known phylum. At the time these were interpreted as evidence that the modern phyla had evolved very rapidly in the "Cambrian explosion" and that the Burgess Shale's "weird wonders" showed that the Early Cambrian was a uniquely experimental period of animal evolution.[142] Later discoveries of similar animals and the development of new theoretical approaches led to the conclusion that many of the "weird wonders" were evolutionary "aunts" or "cousins" of modern groups[143] – for example that *Opabinia* was a member of the lobopods, a group which includes the ancestors of the arthropods, and that it may have been closely related to the modern tardigrades.[144] Nevertheless there is still much debate about whether the Cambrian explosion was really explosive and, if so, how and why it happened and why it appears unique in the history of animals.[145]

Acanthodians were among the earliest vertebrates with jaws[146]

Most of the animals at the heart of the Cambrian explosion debate are protostomes, one of the two main groups of complex animals. One deuterostome group, the echinoderms, many of which have hard calcite "shells", are fairly common from the Early Cambrian small shelly fauna onwards.[140] Other deuterostome groups are soft-bodied, and most of the significant Cambrian deuterostome fossils come from the Chengjiang fauna, a lagerstätte in China.[147] The Chengjiang fossils *Haikouichthys* and *Myllokunmingia* appear to be true vertebrates,[148] and *Haikouichthys* had distinct vertebrae, which may have been slightly mineralized.[149] Vertebrates with jaws, such as the Acanthodians, first appeared in the Late Ordovician.[150]

Colonization of land

Adaptation to life on land is a major challenge: all land organisms need to avoid drying-out and all those above microscopic size have to resist gravity; respiration and gas exchange systems have to change; reproductive systems cannot depend on water to carry eggs and sperm towards each other.[151] [152] Although the earliest good evidence of land plants and animals dates back to the Ordovician period (488 to 444 [153] million years ago), modern land ecosystems only appeared in the late Devonian, about 385 to 359 [154] million years ago.[155]

Evolution of soil

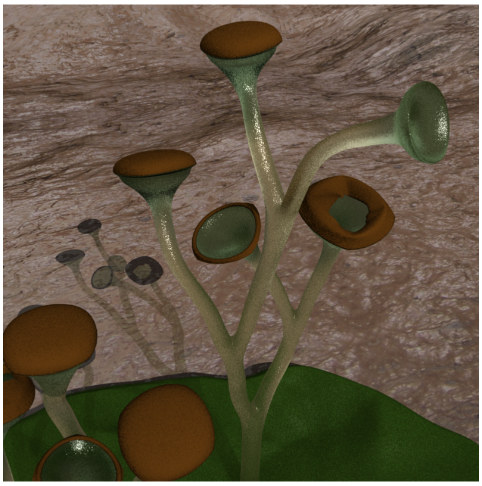
Before the colonization of land, soil, a combination of mineral particles and decomposed organic matter, did not exist. Land surfaces would have been either bare rock or unstable sand produced by weathering. Water and any nutrients in it would have drained away very quickly.[155]

Lichens growing on concrete

Films of cyanobacteria, which are not plants but use the same photosynthesis mechanisms, have been found in modern deserts, and only in areas that are unsuitable for vascular plants. This suggests that microbial mats may have been the first organisms to colonize dry land, possibly in the Precambrian. Mat-forming cyanobacteria could have gradually evolved resistance to desiccation as they spread from the seas to tidal zones and then to land.[155] Lichens, which are symbiotic combinations of a fungus (almost always an ascomycete) and one or more photosynthesizers (green algae or cyanobacteria),[156] are also important colonizers of lifeless environments,[155] and their ability to break down rocks contributes to soil formation in situations where plants cannot survive.[156] The earliest known ascomycete fossils date from 423 to 419 [157] million years ago in the Silurian.[155]

Soil formation would have been very slow until the appearance of burrowing animals, which mix the mineral and organic components of soil and whose feces are a major source of the organic components.[155] Burrows have been found in Ordovician sediments, and are attributed to annelids ("worms") or arthropods.[155] [158]

Plants and the Late Devonian wood crisis



Reconstruction of *Cooksonia*, a vascular plant from the Silurian.

In aquatic algae, almost all cells are capable of photosynthesies and are nearly independent. Life on land required plants to become internally more complex and specialized: photosynthesis was most efficient at the top; roots were required in order to extract water from the ground; the parts in between became supports and transport systems for water and nutrients.[151] [159]

Spores of land plants, possibly rather like liverworts, have been found in Mid Ordovician rocks dated to about 476 [160] million years ago. In Mid Silurian rocks 430 [161] million years ago there are fossils of actual plants including clubmosses such as *Baragwanathia*; most were under 10 centimetres (3.9 in) high, and some appear closely related to vascular plants, the group that includes trees.[159]

By the Late Devonian 370 [162] million years ago, trees such as *Archaeopteris* were so abundant that they changed river systems from mostly braided to mostly meandering, because their roots bound the soil firmly.[163] In fact they caused a "Late Devonian wood crisis",[164] because:

- They removed more carbon dioxide from the atmosphere, reducing the greenhouse effect and thus causing an ice age in the Carboniferous period.[165] In later ecosystems the carbon


Fossilized trees from the Mid-Devonian Gilboa fossil forest.

dioxide "locked up" in wood is returned to the atmosphere by decomposition of dead wood. However the earliest fossil evidence of fungi that can decompose wood also comes from the Late Devonian.[166]

- The increasing depth of plants' roots led to more washing of nutrients into rivers and seas by rain. This caused algal blooms whose high consumption of oxygen caused anoxic events in deeper waters, increasing the extinction rate among deep-water animals.[165]

Land invertebrates

Animals had to change their feeding and excretory systems, and most land animals developed internal fertilization of their eggs. The difference in refractive index between water and air required changes in their eyes. On the other hand in some ways movement and breathing became easier, and the better transmission of high-frequency sounds in air encouraged the development of hearing.[152]

Some trace fossils from the Cambrian-Ordovician boundary about 490.0 [167] million years ago are interpreted as the tracks of large amphibious arthropods on coastal sand dunes, and may have been made by euthycarcinoids,[168] which are thought to be evolutionary "aunts" of myriapods.[169] Other trace fossils from the Late Ordovician a little over 445 [170] million years ago probably represent land invertebrates, and there is clear evidence of numerous arthropods on coasts and alluvial plains shortly before the Silurian-Devonian boundary, about 415 [171] million years ago, including signs that some arthropods ate plants.[172] Arthropods were well pre-adapted to colonise land, because their existing jointed exoskeletons provided protection against desiccation, support against gravity and a means of locomotion that was not dependent on water.[173]

The fossil record of other major invertebrate groups on land is poor: none at all for non-parasitic flatworms, nematodes or nemerteans; some parasitic nematodes have been fossilized in amber; annelid worm fossils are known from the Carboniferous, but they may still have been aquatic animals; the earliest fossils of gastropods on land date from the Late Carboniferous, and this group may have had to wait until leaf litter became abundant enough to provide the moist conditions they need.[152]

The earliest confirmed fossils of flying insects date from the Late Carboniferous, but it is thought that insects developed the ability to fly in the Early Carboniferous or even Late Devonian. This gave them a wider range of ecological niches for feeding and breeding, and a means of escape from predators and from unfavorable changes in the environment.[174] About 99% of modern insect species fly or are descendants of flying species.[175]

Land vertebrates


Acanthostega changed views about the early evolution of tetrapods[176]

"Fish"

Osteolepiformes ("fish")

Panderichthyidae

Obruchevichthidae

Acanthostega

Ichthyostega

Tulerpeton

Early amphibians

Anthracosauria

Amniotes

Family tree of tetrapods[177]

Tetrapods, vertebrates with four limbs, evolved from other rhipidistians over a relatively short timespan during the Late Devonian, between 370 [162] million years ago and 360 [178] million years ago.[179] From the 1950s to the early 1980s it was thought that tetrapods evolved from fish that had already acquired the ability to crawl on land, possibly in order to go from a pool that was drying out to one that was deeper. However in 1987 nearly-complete fossils of *Acanthostega* from about 363 [180] million years ago showed that this Late Devonian transitional animal had legs and both lungs and gills, but could never have survived on land: its limbs and its wrist and ankle joints were too weak to bear its weight; its ribs were too short to prevent its lungs from being squeezed flat by its weight; its fish-like tail fin would have been damaged by dragging on the ground. The current hypothesis is that *Acanthostega*, which was about 1 metre (3.3 ft) long, was a wholly aquatic predator that hunted in shallow water. Its skeleton differed from that of most fish, in ways that enabled it to raise its head to breathe air while its body remained submerged, including: its jaws show modifications that would have enabled it to gulp air; the bones at the back of its skull are locked together, providing strong attachment points for muscles that raised its head; the head is not joined to the shoulder girdle and it has a distinct neck.[176]

The Devonian proliferation of land plants may help to explain why air-breathing would have been an advantage: leaves falling into streams and rivers would have encouraged the growth of aquatic vegetation; this would have attracted grazing invertebrates and small fish that preyed on them; they would have been attractive prey but the environment was unsuitable for the big marine predatory fish; air-breathing would have been necessary because these waters would have been short of oxygen, since warm water holds less dissolved oxygen than cooler marine water and since the decomposition of vegetation would have used some of the oxygen.[176]

Later discoveries revealed earlier transitional forms between *Acanthostega* and completely fish-like animals.[181] Unfortunately there is then a gap of about 30 million years between the fossils of ancestral tetrapods and Mid Carboniferous fossils of vertebrates that look well-adapted for life on land. Some of these look like early relatives of modern amphibians, most of which need to keep their skins moist and to lay their eggs in water, while others are

accepted as early relatives of the amniotes, whose water-proof skins and eggs enable them to live and breed far from water.[177]

Dinosaurs, birds and mammals

Amniotes

Synapsids

Early synapsids (extinct)

Pelycosaurs

Extinct pelycosaurs

Therapsids

Extinct therapsids

Mammaliformes

Extinct mammaliformes

Mammals

Sauropsids

Anapsids; whether turtles belong here is debated[182]

Captorhinidae and Protorothyrididae

Diapsids

Araeoscelidia (extinct)

Squamata (lizards and snakes)

Archosaurs

Extinct archosaurs

Crocodilians

Pterosaurs (extinct)

Dinosaurs

Theropods

Extinct theropods

Birds

Sauropods (extinct)

Ornithischians (extinct)

Possible family tree of dinosaurs, birds and mammals[183] [184]

Amniotes, whose eggs can survive in dry environments, probably evolved in the Late Carboniferous period, between 330 [185] million years ago and 314 [186] million years ago. The earliest fossils of the two surviving amniote groups, synapsids and sauropsids, date from around 313 [187] million years ago.[183] [184] The synapsid pelycosaurs and their descendants the therapsids are the most common land vertebrates in the best-known Permian fossil beds, between 229.0 [188] million years ago and 251.0 [17] million years ago. However at the time these were all in temperate zones at middle latitudes, and there is evidence that hotter, drier environments nearer the Equator were dominated by sauropsids and amphibians.[189]

The Permian-Triassic extinction wiped out almost all land vertebrates,[190] as well as the great majority of other life.[191] During the slow recovery from this catastrophe, estimated to be 30M years,[192] a previously obscure sauropsid group became the most abundant and diverse terrestrial vertebrates: a few fossils of archosauriformes ("shaped like archosaurs") have been found in Late Permian rocks,[193] but by the Mid Triassic archosaurs were the dominant land vertebrates. Dinosaurs distinguished themselves from other archosaurs in the Late Triassic, and became the dominant land vertebrates of the Jurassic and Cretaceous periods, between 199 [194] million years ago and 65 [22] million years ago.[195]

During the Late Jurassic, birds evolved from small, predatory theropod dinosaurs.[196] The first birds inherited teeth and long, bony tails from their dinosaur ancestors,[196] but some developed horny, toothless beaks by the very Late Jurassic[197] and short pygostyle tails by the Early Cretaceous.[198]

While the archosaurs and dinosaurs were becoming more dominant in the Triassic, the mammaliform successors of the therapsids could only survive as small, mainly nocturnal insectivores. This apparent set-back may actually have promoted the evolution of mammals, for example nocturnal life may have accelerated the development of endothermy ("warm-bloodedness") and hair or fur.[199] By 195 [200] million years ago in the Early Jurassic there were animals that were very nearly mammals.[201] Unfortunately there is a gap in the fossil record throughout the Mid Jurassic.[202] However fossil teeth discovered in Madagascar indicate that true mammals existed at least 167 [203] million years ago.[204] After dominating land vertebrate niches for about 150 million years, the dinosaurs perished 65 [22] million years ago in the Cretaceous–Tertiary extinction along with many other groups of organisms.[205] Mammals throughout the time of the dinosaurs had been restricted to a narrow range of taxa, sizes and shapes, but increased rapidly in size and diversity after the extinction,[206] [207] with bats taking to the air within 13 million years,[208] and cetaceans to the sea within 15 million years.[209]

Flowering plants

Gymnosperms

Gnetales (gymnosperm)

Welwitschia (gymnosperm)

Ephedra (gymnosperm)

Bennettitales

Angiosperms (flowering plants)

One possible family tree of flowering plants.[210]

Gymnosperms

Angiosperms (flowering plants)

Cycads (gymnosperm)

Bennettitales

Gingko

Gnetales (gymnosperm)

Conifers (gymnosperm)

Another possible family tree.[211]

The 250,000 to 400,000 species of flowering plants outnumber all other ground plants combined, and are the dominant vegetation in most terrestrial ecosystems. There is fossil evidence that flowering plants diversified rapidly in the Early Cretaceous, between 130 [26] million years ago and 90 [27] million years ago,[210] [211] and that their rise was associated with that of pollinating insects.[211] Among modern flowering plants Magnolias are thought to be close to the common ancestor of the group.[210] However paleontologists have not succeeded in identifying the earliest stages in the evolution of flowering plants.[210] [211]

Social insects

The social insects are remarkable because the great majority of individuals in each colony are sterile. This appears contrary to basic concepts of evolution such as natural selection and the selfish gene. In fact there are very few eusocial insect species: only 15 out of approximately 2,600 living families of insects contain eusocial species, and it seems that eusociality has evolved independently only 12 times among arthropods, although some eusocial lineages have diversified into several families. Nevertheless social insects have been spectacularly successful; for example although ants and termites account for only about 2% of known insect species, they form over 50% of the total mass of insects. Their ability to control a territory appears to be the foundation of their success.[212]

The sacrifice of breeding opportunities by most individuals has long been explained as a consequence of these species' unusual haplodiploid method of sex determination, which has the paradoxical consequence that two sterile worker daughters of the same queen share more genes with each other than they would with their offspring if they could breed.[213] However Wilson and Hölldobler argue that this explanation is faulty: for example, it is based on kin selection, but there is no evidence of nepotism in colonies that have multiple queens. Instead, they write, eusociality evolves only in species that are under strong pressure from predators and competitors, but in environments where it is possible to build "fortresses"; after colonies have established this security, they gain other advantages though co-operative foraging. In support of this explanation they cite the appearance of eusociality in bathyergid mole rats,[212] which are not haplodiploid.[214]

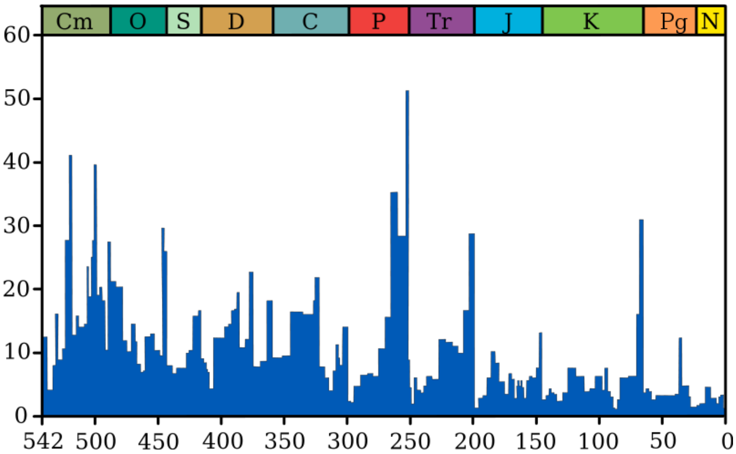

These termite mounds have survived a bush fire.

The earliest fossils of insects have been found in Early Devonian rocks from about 400 [215] million years ago, which preserve only a few varieties of flightless insect. The Mazon Creek lagerstätten from the Late Carboniferous, about 300 [216] million years ago, include about 200 species, some gigantic by modern standards, and indicate that insects had occupied their main modern ecological niches as herbivores, detritivores and insectivores. Social termites and ants first appear in the Early Cretaceous, and advanced social bees have been found in Late Cretaceous rocks but did not become abundant until the Mid Cenozoic.[217]

Humans

Modern humans evolved from a lineage of upright-walking apes that has been traced back over 6 [28] million years ago to *Sahelanthropus*.[218] The first known stone tools were made about 2.5 [219] million years ago, apparently by *Australopithecus garhi*, and were found near animal bones that bear scratches made by these tools.[220] The earliest hominines had chimp-sized brains, but there has been a fourfold increase in the last 3 million years; a statistical analysis suggests that hominine brain sizes depend almost completely on the date of the fossils, while the species to which they are assigned has only slight influence.[221] There is a long-running debate about whether modern humans evolved all over the world simultaneously from existing advanced hominines or are descendants of a single small population in Africa, which then migrated all over the world less than 200,000 years ago and replaced previous hominine species.[222] There is also debate about whether anatomically-modern humans had an intellectual, cultural and technological "Great Leap Forward" under 100,000 years ago and, if so, whether this was due to neurological changes that are not visible in fossils.[223]

Mass extinctions



K–T

Tr–J

P–Tr

Late D

O–S

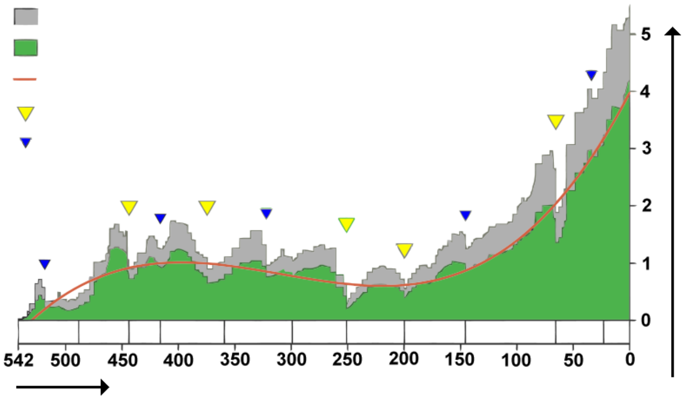
Millions of years ago

Apparent extinction intensity, i.e. the fraction of genera going extinct at any given time, as reconstructed from the fossil record. (Graph not meant to include recent epoch of Holocene extinction event)

Life on earth has suffered occasional mass extinctions at least since 542 [224] million years ago. Although they are disasters at the time, mass extinctions have sometimes accelerated the evolution of life on earth. When dominance of particular ecological niches passes from one group of organisms to another, it is rarely because the new dominant group is "superior" to the old and usually because an extinction event eliminates the old dominant group and makes way for the new one.[225] [226]

The fossil record appears to show that the gaps between mass extinctions are becoming longer and the average and background rates of extinction are decreasing. Both of these phenomena could be explained in one or more ways:[227]

- The oceans may have become more hospitable to life over the last 500 million years and less vulnerable to mass extinctions: dissolved oxygen became more widespread and penetrated to greater depths; the development of life on land reduced the run-off of nutrients and hence the risk of eutrophication and anoxic events; and marine ecosystems became more diversified so that food chains were less likely to be disrupted.[228] [229]
- Reasonably complete fossils are very rare, most extinct organisms are represented only by partial fossils, and complete fossils are rarest in the oldest rocks. So paleontologists have mistakenly assigned parts of the same organism to different genera which were often defined solely to accommodate these finds – the story of *Anomalocaris* is an example of this. The risk of this mistake is higher for older fossils because these are often unlike parts of any living organism. Many of the "superfluous" genera are represented by fragments which are not found again and the "superfluous" genera appear to become extinct very quickly.[227]



All genera

"Well-defined" genera

Trend line

"Big Five" mass extinctions

Other mass extinctions

Million years ago

Thousands of genera

Phanerozoic biodiversity as shown by the fossil record

Biodiversity in the fossil record, which is

> "the number of distinct genera alive at any given time; that is, those whose first occurrence predates and whose last occurrence postdates that time"[230]

shows a different trend: a fairly swift rise from 542 to 400 [231] million years ago; a slight decline from 400 to 200 [232] million years ago, in which the devastating Permian–Triassic extinction event is an important factor; and a swift rise from 200 [233] million years ago to the present.[230]

The present

Oxygenic photosynthesis accounts for virtually all of the production of organic matter from non-organic ingredients. Production is split about evenly between land and marine plants, and phytoplankton are the dominant marine producers.[234]

The processes that drive evolution are still operating. Well-known examples include the changes in coloration of the peppered moth over the last 200 years and the more recent appearance of pathogens that are resistant to antibiotics.[235] [236] There is even evidence that humans are still evolving, and possibly at an accelerating rate over the last 40,000 years.[237]

See also

- Evolution
- Evolutionary history of plants
- Timeline of evolution
- History of evolutionary thought

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External links

General information

- General information on evolution- Fossil Museum nav. [238]
- Understanding Evolution from University of California, Berkeley [239]
- National Academies Evolution Resources [240]
- Evolution poster- PDF format "tree of life" [241]
- Everything you wanted to know about evolution by *New Scientist* [242]
- Howstuffworks.com — How Evolution Works [243]
- Synthetic Theory Of Evolution: An Introduction to Modern Evolutionary Concepts and Theories [244]

History of evolutionary thought

- The Complete Work of Charles Darwin Online [245]
- Understanding Evolution: History, Theory, Evidence, and Implications [246]

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Modern evolutionary synthesis

The **modern evolutionary synthesis** is also referred to as the **new synthesis**, the **modern synthesis**, the **evolutionary synthesis** and the **neo-darwinian synthesis**. It is a union of ideas from several biological specialties which provides a widely accepted account of evolution. The synthesis has been accepted by nearly all working biologists.[1] The synthesis was produced over a decade (1936–1947). The previous development of population genetics (1918–1932) was a stimulus, as it showed that Mendelian genetics was consistent with natural selection and gradual evolution. The synthesis is still, to a large extent, the current paradigm in evolutionary biology.[2]

Julian Huxley invented the term, when he produced his book, *Evolution: The Modern Synthesis* (1942). Other major figures in the modern synthesis include R. A. Fisher, Theodosius Dobzhansky, J.B.S. Haldane, Sewall Wright, E.B. Ford, Ernst Mayr, Bernhard Rensch, Sergei Chetverikov, George Gaylord Simpson, and G. Ledyard Stebbins.

The modern synthesis solved difficulties and confusions caused by the specialisation and poor communication between biologists in the early years of the 20th century. Discoveries of early geneticists were difficult to reconcile with gradual evolution and the mechanism of natural selection. The synthesis reconciled the two schools of thought, while providing evidence that studies of populations in the field were crucial to evolutionary theory. It drew together ideas from several branches of biology that had become separated, particularly genetics, cytology, systematics, botany, morphology, ecology and paleontology.

Summary of the modern synthesis

The modern synthesis bridged the gap between experimental geneticists and naturalists, and between both and palaeontologists. It states that:[3] [4] [5]

1. All evolutionary phenomena can be explained in a way consistent with known genetic mechanisms and the observational evidence of naturalists.
2. Evolution is gradual: small genetic changes, recombination ordered by natural selection. Discontinuities amongst species (or other taxa) are explained as originating gradually through geographical separation and extinction (not saltation).
3. Natural selection is by far the main mechanism of change; even slight advantages are important when continued. The object of selection is the phenotype in its surrounding environment.
4. The role of genetic drift is equivocal. Though strongly supported initially by Dobzhansky, it was downgraded later as results from ecological genetics were obtained.
5. Thinking in terms of populations, rather than individuals, is primary: the genetic diversity existing in natural populations is a key factor in evolution. The strength of natural selection in the wild is greater than previously expected; the effect of ecological factors such as niche occupation and the significance of barriers to gene flow are all important.
6. In palaeontology, the ability to explain historical observations by extrapolation from microevolution to macroevolution is proposed. Historical contingency means explanations at different levels may exist. Gradualism does not mean constant rate of change.

The idea that speciation occurs after populations are reproductively isolated has been much debated. In plants, polyploidy must be included in any view of speciation. Formulations such as 'evolution consists primarily of changes in the frequencies of alleles between one generation and another' were proposed rather later. The traditional view is that developmental biology ('evo-devo') played little part in the synthesis,[6] but an account of Gavin de Beer's work by Stephen J. Gould suggests he may be an exception.[7]

Developments leading up to the synthesis

1859–1899

Charles Darwin's *The Origin of Species* was successful in convincing most biologists that evolution had occurred, but was less successful in convincing them that natural selection was its primary mechanism. In the 19th and early 20th centuries, variations of Lamarckism, orthogenesis ('progressive' evolution), and saltationism (evolution by jumps) were discussed as alternatives.[8] Also, Darwin did not offer a precise explanation of how new species arise. As part of the disagreement about whether natural selection alone was sufficient to explain speciation, George Romanes coined the term neo-Darwinism to refer to the version of evolution advocated by Alfred Russel Wallace and August Weismann with its heavy dependence on natural selection.[9] Weismann and Wallace rejected the Lamarckian idea of inheritance of acquired characteristics, something that Darwin had not ruled out.[10]

Weismann's idea was that the relationship between the hereditary material, which he called the germ plasm (de: *Keimplasma*), and the rest of the body (the soma) was a one-way relationship: the germ-plasm formed the body, but the body did not influence the germ-plasm, except indirectly in its participation in a population subject to natural selection. Weismann was translated into English, and though he was influential, it took many years for the full significance of his work to be appreciated.[11] Later, after the completion of the modern synthesis, the term neo-Darwinism came to be associated with its core concept: evolution, driven by natural selection acting on variation produced by genetic mutation, and recombination (chromosomal crossovers).[9]

1900–1915

Gregor Mendel's work was re-discovered by Hugo de Vries and Carl Correns in 1900. News of this reached William Bateson in England, who reported on the paper during a presentation to the Royal Horticultural Society in May 1900.[12] It showed that the contributions of each parent retained their integrity rather than blending with the contribution of the other parent. This reinforced a division of thought, which was already present in the 1890s.[13] The two schools were:

- Saltationism (large mutations or jumps), favored by early Mendelians who viewed hard inheritance as incompatible with natural selection[14]
- Biometric school: led by Karl Pearson and Walter Weldon, argued vigorously against it, saying that empirical evidence indicated that variation was continuous in most organisms, not discrete as Mendelism predicted.

The relevance of Mendelism to evolution was unclear and hotly debated, especially by Bateson, who opposed the biometric ideas of his former teacher Weldon. Many scientists believed the two theories substantially contradicted each other.[15] This debate between the biometricians and the Mendelians continued for some 20 years and was only solved by the development of population genetics.

T. H. Morgan began his career in genetics as a saltationist, and started out trying to demonstrate that mutations could produce new species in fruit flies. However, the experimental work at his lab with *Drosophila melanogaster*, which helped establish the link between Mendelian genetics and the chromosomal theory of inheritance, demonstrated that rather than creating new species in a single step, mutations increased the genetic variation in the population.[16]

The foundation of population genetics

The first step towards the synthesis was the development of population genetics. R.A. Fisher, J.B.S. Haldane, and Sewall Wright provided critical contributions. In 1918, Fisher produced the paper "The Correlation Between Relatives on the Supposition of Mendelian Inheritance",[17] which showed how the continuous variation measured by the biometricians could be the result of the action of many discrete genetic loci. In this and subsequent papers culminating in his 1930 book *The Genetical Theory of Natural Selection*, Fisher was able to show how Mendelian genetics was, contrary to the thinking of many early geneticists, completely consistent with the idea of evolution driven by natural selection.[18] During the 1920s, a series of papers by J.B.S. Haldane applied mathematical analysis

to real world examples of natural selection such as the evolution of industrial melanism in peppered moths.[] Haldane established that natural selection could work in the real world at a faster rate than even Fisher had assumed.[19]

Sewall Wright focused on combinations of genes that interacted as complexes, and the effects of inbreeding on small relatively isolated populations, which could exhibit genetic drift. In a 1932 paper he introduced the concept of an adaptive landscape in which phenomena such as cross breeding and genetic drift in small populations could push them away from adaptive peaks, which would in turn allow natural selection to push them towards new adaptive peaks.[] Wright's model would appeal to field naturalists such as Theodosius Dobzhansky and Ernst Mayr who were becoming aware of the importance of geographical isolation in real world populations.[19] The work of Fisher, Haldane and Wright founded the discipline of population genetics. This is the precursor of the modern synthesis, which is an even broader coalition of ideas.[] [19] [20]

The modern synthesis

Theodosius Dobzhansky, a Ukrainian émigré who had been a postdoctoral worker in Morgan's fruit fly lab, was one of the first to apply genetics to natural populations. He worked mostly with *Drosophila pseudoobscura*. He says pointedly: "Russia has a variety of climates from the Arctic to sub-tropical... Exclusively laboratory workers who neither possess nor wish to have any knowledge of living beings in nature were and are in a minority".[21] Not surprisingly, there were other Russian geneticists with similar ideas, though for some time their work was known to only a few in the West. His 1937 work *Genetics and the Origin of Species* was a key step in bridging the gap between population geneticists and field naturalists. It presented the conclusions reached by Fisher, Haldane, and especially Wright in their highly mathematical papers in a form that was easily accessible to others. It also emphasized that real world populations had far more genetic variability than the early population geneticists had assumed in their models, and that genetically distinct sub-populations were important. Dobzhansky argued that natural selection worked to maintain genetic diversity as well as driving change. Dobzhansky had been influenced by his exposure in the 1920s to the work of a Russian geneticist named Sergei Chetverikov who had looked at the role of recessive genes in maintaining a reservoir of genetic variability in a population before his work was shut down by the rise of Lysenkoism in the Soviet Union.[] [19]

Edmund Brisco Ford's work complemented that of Dobzhansky. It was as a result of Ford's work, as well as his own, that Dobzhansky changed the emphasis in the third edition of his famous text from drift to selection.[22] Ford was an experimental naturalist who wanted to test natural selection in nature. He virtually invented the field of research known as ecological genetics. His work on natural selection in wild populations of butterflies and moths was the first to show that predictions made by R.A. Fisher were correct. He was the first to describe and define genetic polymorphism, and to predict that human blood group polymorphisms might be maintained in the population by providing some protection against disease.[23]

Ernst Mayr's key contribution to the synthesis was *Systematics and the Origin of Species*, published in 1942. Mayr emphasized the importance of allopatric speciation, where geographically isolated sub-populations diverge so far that reproductive isolation occurs. He was sceptical of the reality of sympatric speciation believing that geographical isolation was a prerequisite for building up intrinsic (reproductive) isolating mechanisms. Mayr also introduced the biological species concept that defined a species as a group of interbreeding or potentially interbreeding populations that were reproductively isolated from all other populations.[] [19] [24] Before he left Germany for the United States in 1930, Mayr had been influenced by the work of German biologist Bernhard Rensch. In the 1920s Rensch, who like Mayr did field work in Indonesia, analyzed the geographic distribution of polytypic species and complexes of closely related species paying particular attention to how variations between different populations correlated with local environmental factors such as differences in climate. In 1947, Rensch published *Neuere Probleme der Abstammungslehre: die Transspezifische Evolution* (English translation 1959: *Evolution above the Species level*). This looked at how the same evolutionary mechanisms involved in speciation might be extended to explain the origins of the differences between the higher level taxa. His writings contributed to the rapid acceptance of the

synthesis in Germany.[25] [26]

George Gaylord Simpson was responsible for showing that the modern synthesis was compatible with paleontology in his book *Tempo and Mode in Evolution* published in 1944. Simpson's work was crucial because so many paleontologists had disagreed, in some cases vigorously, with the idea that natural selection was the main mechanism of evolution. It showed that the trends of linear progression (in for example the evolution of the horse) that earlier paleontologists had used as support for neo-Lamarckism and orthogenesis did not hold up under careful examination. Instead the fossil record was consistent with the irregular, branching, and non-directional pattern predicted by the modern synthesis.[] [19]

The botanist G. Ledyard Stebbins was another major contributor to the synthesis. His major work, *Variation and Evolution in Plants*, was published in 1950. It extended the synthesis to encompass botany including the important effects of hybridization and polyploidy in some kinds of plants.[]

Further advances

The modern evolutionary synthesis continued to be developed and refined after the initial establishment in the 1930s and 1940s. The work of W. D. Hamilton, George C. Williams, John Maynard Smith and others led to the development of a gene-centric view of evolution in the 1960s. The synthesis as it exists now has extended the scope of the Darwinian idea of natural selection to include subsequent scientific discoveries and concepts unknown to Darwin, such as DNA and genetics, which allow rigorous, in many cases mathematical, analyses of phenomena such as kin selection, altruism, and speciation.

A particular interpretation most commonly associated with Richard Dawkins, author of *The Selfish Gene*, asserts that the gene is the only true unit of selection.[27] Dawkins further extended the Darwinian idea to include non-biological systems exhibiting the same type of selective behavior of the 'fittest' such as memes in culture. The synthesis continues to undergo regular review.[28] See also Current research in evolutionary biology

After the synthesis

There are a number of discoveries in earth sciences and biology which have arisen since the synthesis. Listed here are some of those topics which are relevant to the evolutionary synthesis, and which seem soundly based.

Understanding of Earth history

The Earth is the stage on which the evolutionary play is performed. Darwin studied evolution in the context of Charles Lyell's geology, but our present understanding of Earth history includes some critical advances made during the last half-century.

- The age of the Earth has been revised upwards. It is now estimated at 4.56 billion years, about one-third of the age of the universe. It is worth noting that the Phanerozoic only occupies the last 1/9th of this period of time.[29]
- The triumph of Alfred Wegener's idea of continental drift came around 1960. The key principle of plate tectonics is that the lithosphere exists as separate and distinct tectonic plates, which ride on the fluid-like (visco-elastic solid) asthenosphere. This discovery provides a unifying theory for geology, linking phenomena such as volcanos, earthquakes, orogeny, and providing data for many paleogeographical questions.[30] One major question is still unclear: when did plate tectonics begin?[31]
- Our understanding of the evolution of the Earth's atmosphere has progressed. The substitution of oxygen for carbon dioxide in the atmosphere, which occurred in the Proterozoic, caused probably by cyanobacteria in the form of stromatolites, caused changes leading to the evolution of aerobic organisms.[32] [33]
- The identification of the first generally accepted fossils of microbial life was made by geologists. These rocks have been dated as about 3.465 billion years ago.[34] Walcott was the first geologist to identify pre-Cambrian fossil bacteria from microscopic examination of thin rock slices. He also thought stromatolites were organic in

origin. His ideas were not accepted at the time, but may now be appreciated as great discoveries.[35]

- Information about paleoclimates is increasingly available, and being used in paleontology. One example: the discovery of massive ice ages in the Proterozoic, following the great reduction of CO_2 in the atmosphere. These ice ages were immensely long, and led to a crash in microflora.[36] See also Cryogenian period and Snowball Earth.
- Catastrophism and mass extinctions. A partial reintegration of catastrophism has occurred,[37] and the importance of mass extinctions in large-scale evolution is now apparent. Extinction events disturb relationships between many forms of life and may remove dominant forms and release a flow of adaptive radiation amongst groups that remain. Causes include meteorite strikes (K–T junction; Upper Devonian); flood basalt provinces (Deccan traps at K/T junction; Siberian traps at P–T junction); and other less dramatic processes.[38] [39]

Conclusion: Our present knowledge of earth history strongly suggests that large-scale geophysical events influenced macroevolution and megaevolution. These terms refer to evolution above the species level, including such events as mass extinctions, adaptive radiation, and the major transitions in evolution.[40] [41]

Symbiotic origin of eukaryotic cell structures

Once symbiosis was discovered in lichen and in plant roots (rhizobia in root nodules) in the 19th century, the idea arose that the process might have occurred more widely, and might be important in evolution. Anton de Bary invented the concept of *symbiosis*;[42] several Russian biologists promoted the idea;[43] Edwin Wilson mentioned it in his epic text *The Cell*;[44] a book was published in the U.S.A. in 1927 with the title *Symbionticism and the origin of species*;[45] and there was a brief mention by Julian Huxley in 1930;[46] all in vain because sufficient evidence was lacking. Symbiosis as a major evolutionary force was not discussed at all in the evolutionary synthesis.[47]

The role of symbiosis in cell evolution was revived partly by Joshua Lederberg,[48] and finally brought to light by Lynn Margulis in a series of papers and books.[49] [50] It turns out that some cell organelles are of microbial origin: mitochondria and chloroplasts definitely, cilia, flagella and centrioles possibly, and perhaps the nuclear membrane and much of the chromosome structure as well. What is now clear is that the evolution of eukaryote cells is either caused by, or at least profoundly influenced by, symbiosis with bacterial and archaean cells in the Proterozoic.

The origin of the eukaryote cell by symbiosis in several stages was not part of the evolutionary synthesis. It is, at least on first sight, an example of megaevolution by big jumps. However, what symbiosis provided was a copious supply of heritable variation from microorganisms, which was fine-tuned over a long period to produce the cell structure we see today. This part of the process is consistent with evolution by natural selection.[51]

Trees of life

The ability to analyse sequence in macromolecules (protein, DNA, RNA) provides evidence of descent, and permits us to work out genealogical trees covering the whole of life, since now there are data on every major group of living organisms. This project, begun in a tentative way in the 1960s, has become a search for the universal tree or the universal ancestor, a phrase of Carl Woese.[52] [53] The tree that results has some unusual features, especially in its roots. There are two kingdoms of prokaryotes: bacteria and archaea, both of which contributed genetic material to the eukaryotes, mainly by means of symbiosis. Also, since bacteria can pass genetic material to other bacteria, their relationships look more like a web than a tree. Once eukaryotes were established, their sexual reproduction produced the traditional branching tree-like pattern, the only diagram Darwin put in the *Origin*. The last universal common ancestor (LUCA) would be a prokaryotic cell before the split between the bacteria and archaea. LUCA is defined as most recent organism from which all organisms now living on Earth descend (some 3.5 to 3.8 billion years ago, in the Archean era).[54]

This technique may be used to clarify relationships within any group of related organisms. It is now a standard procedure, and examples are published regularly. April 2009 sees the publication of a tree covering all the animal phyla, derived from sequences from 150 genes in 77 taxa.[55]

Early attempts to identify relationships between major groups were made in the 19th century by Ernst Haeckel, and by comparative anatomists such as Thomas Henry Huxley and E. Ray Lankester. Enthusiasm waned: it was often difficult to find evidence to adjudicate between different opinions. Perhaps for that reason, the evolutionary synthesis paid surprisingly little attention to this activity. It is certainly a lively field of research today.

Evo-devo

What once was called embryology played a modest role in the evolutionary synthesis,[56] mostly about evolution by changes in developmental timing (allometry and heterochrony).[57] Man himself was, according to Bolk, a typical case of evolution by retention of juvenile characteristics (neoteny). He listed many characters where "Man, in his bodily development, is a primate foetus that has become sexually mature".[58] Unfortunately, his interpretation of these ideas was non-Darwinian, but his list of characters is both interesting and convincing.[59]

Modern interest in Evo-devo springs from clear proof that development is closely controlled by special genetic systems, and the hope that comparison of these systems will tell us much about the evolutionary history of different groups.[60] [61] In a series of experiments with the fruit-fly *Drosophila*, Edward B. Lewis was able to identify a complex of genes whose proteins bind to the cis-regulatory regions of target genes. The latter then activate or repress systems of cellular processes that accomplish the final development of the organism.[62] [63] Furthermore, the sequence of these control genes show *co-linearity*: the order of the loci in the chromosome parallels the order in which the loci are expressed along the anterior-posterior axis of the body. Not only that, but this cluster of master control genes programs the development of all higher organisms.[64] [65] Each of the genes contains a homeobox, a remarkably conserved DNA sequence. This suggests the complex itself arose by gene duplication.[66] [67] [68] In his Nobel lecture, Lewis said "Ultimately, comparisons of the [control complexes] throughout the animal kingdom should provide a picture of how the organisms, as well as the [control genes] have evolved".

The term *deep homology* was coined to describe the common origin of genetic regulatory apparatus used to build morphologically and phylogenetically disparate animal features.[69] It applies when a complex genetic regulatory system is inherited from a common ancestor, as it is in the evolution of vertebrate and invertebrate eyes. The phenomenon is implicated in many cases of parallel evolution.[70]

A great deal of evolution may take place by changes in the control of development. This may be relevant to punctuated equilibrium theory, for in development a few changes to the control system could make a significant difference to the adult organism. An example is the giant panda, whose place in the mammalia was long uncertain.[71] Apparently, the giant panda's evolution from Ursus to Ailuropoda required the change of only a few genetic messages (5 or 6 perhaps), yet the phenotypic and lifestyle change from a standard bear is considerable.[72] [73] The transition could therefore be effected relatively swiftly.

Fossil discoveries

In the past thirty or so years there have been excavations in parts of the world which had scarcely been investigated before. Also, there is fresh appreciation of fossils discovered in the 19th century, but then denied or deprecated: the classic example is the Ediacaran biota from the immediate pre-Cambrian, after the Cryogenian period. These soft-bodied fossils are the first record of multicellular life. The interpretation of this fauna is still in flux.

Many outstanding discoveries have been made, and some of these have implications for evolutionary theory. The discovery of feathered dinosaurs and early birds from the Lower Cretaceous of Liaoning, N.E. China have convinced most students that birds did evolve from coelurosaurian theropod dinosaurs. Less well known, but perhaps of equal evolutionary significance, are the studies on early insect flight, on stem tetrapods from the Upper Devonian,[74] [75] and the early stages of whale evolution.[76]

A shaft of light has been thrown on the evolution of flatfish (pleuronectiformes), such as plaice, sole, turbot and halibut, by recent work. Flatfish are interesting because they are one of the few vertebrate groups with external asymmetry. Their young are perfectly symmetrical, but the head is remodelled during a metamorphosis, which

entails the migration of one eye to the other side, close to the other eye. Some species have both eyes on the left (turbot), some on the right (halibut, sole); all living and fossil flatfish to date show an 'eyed' side and a 'blind' side.[77] The lack of an intermediate condition in living and fossil flatfish species had led to debate about the origin of such a striking adaptation. The case was considered by Lamark,[78] who thought flatfish precursors would have lived in shallow water for a long period, and by Darwin, who predicted a gradual migration of the eye, mirroring the metamorphosis of the living forms. Darwin's long-time critic St. George Mivart thought that the intermediate stages could have no selective value,[79] and in the 6th edition of the *Origin*, Darwin made a concession to the possibility of acquired traits.[80] Many years later the geneticist Richard Goldschmidt put the case forward as an example of evolution by saltation, bypassing intermediate forms.[81] [82]

A recent examination of two fossil species from the Eocene has provided the first clear picture of flatfish evolution. The discovery of stem flatfish with incomplete orbital migration refutes Goldschmidt's ideas, and demonstrates that "the assembly of the flatfish bodyplan occurred in a gradual, stepwise fashion".[83] There are no grounds for thinking that incomplete orbital migration was maladaptive, because stem forms with this condition ranged over two geological stages, and are found in localities which also yield flatfish with the full cranial asymmetry. The evolution of flatfish falls squarely within the evolutionary synthesis.[84]

See also

- Evolution
- The Origin of Species
- History of evolutionary thought
- Gene-centered view of evolution
- Particulate inheritance theory
- Population genetics
- Developmental systems theory
- Polymorphism (biology)

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Population genetics

Population genetics is the study of allele frequency distribution and change under the influence of the four main evolutionary processes: natural selection, genetic drift, mutation and gene flow. It also takes into account the factors of population subdivision and population structure. It attempts to explain such phenomena as adaptation and speciation.

Population genetics was a vital ingredient in the emergence of the modern evolutionary synthesis. Its primary founders were Sewall Wright, J. B. S. Haldane and R. A. Fisher, who also laid the foundations for the related discipline of quantitative genetics.

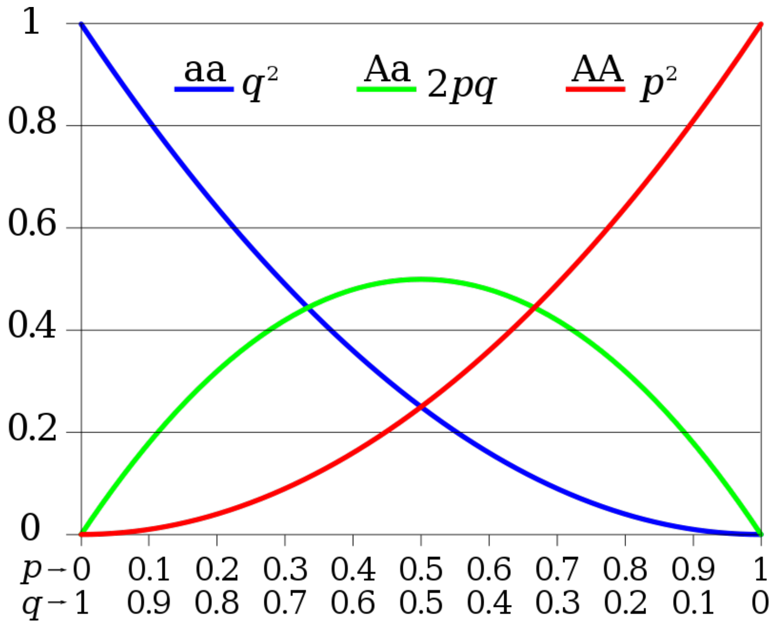
Fundamentals

Population genetics concerns the genetic constitution of populations and how this constitution changes with time. A population is a set of organisms in which any pair of members can breed together. This implies that all members belong to the same species and live near each other.[1]

For example, all of the moths of the same species living in an isolated forest are a population. A gene in this population may have several alternate forms, which account for variations between the phenotypes of the organisms. An example might be a gene for coloration in moths that has two alleles: black and white. A gene pool is the complete set of alleles for a gene in a single population; the allele frequency for an allele is the fraction of the genes in the pool that is composed of that allele (for example, what fraction of moth coloration genes are the black allele). Evolution occurs when there are changes in the frequencies of alleles within a population of interbreeding organisms; for example, the allele for black color in a population of moths becoming more common.

To understand the mechanisms that cause a population to evolve, it is useful to consider what conditions are required for a population not to evolve. The *Hardy-Weinberg principle* states that the frequencies of alleles (variations in a gene) in a sufficiently large population will remain constant if the only forces acting on that population are the random reshuffling of alleles during the formation of the sperm or egg, and the random combination of the alleles in these sex cells during fertilization.[2] Such a population is said to be in *Hardy-Weinberg equilibrium* as it is not evolving.[3]

Hardy–Weinberg principle



Hardy–Weinberg principle for two alleles: the horizontal axis shows the two allele frequencies p and q and the vertical axis shows the genotype frequencies. Each graph shows one of the three possible genotypes.

The *Hardy–Weinberg principle* states that both allele and genotype frequencies in a population remain constant—that is, they are in equilibrium—from generation to generation unless specific disturbing influences are introduced. Outside the lab, one or more of these "disturbing influences" are always in effect. Hardy Weinberg equilibrium is impossible in nature. Genetic equilibrium is an ideal state that provides a baseline to measure genetic change against.

Allele frequencies in a population remain static across generations, provided the following conditions are at hand: random mating, no mutation (the alleles don't change), no migration or emigration (no exchange of alleles between populations), infinitely large population size, and no selective pressure for or against any traits.

In the simplest case of a single locus with two alleles: the dominant allele is denoted **A** and the recessive **a** and their frequencies are denoted by p and q; freq(**A**) = p; freq(**a**) = q; $p + q = 1$. If the population is in equilibrium, then we will have freq(**AA**) = p^2 for the **AA** homozygotes in the population, freq(**aa**) = q^2 for the **aa** homozygotes, and freq(**Aa**) = $2pq$ for the heterozygotes.

Based on these equations, useful but difficult-to-measure facts about a population can be determined. For example, a patient's child is a carrier of a recessive mutation that causes cystic fibrosis in homozygous recessive children. The parent wants to know the probability of her grandchildren inheriting the disease. In order to answer this question, the genetic counselor must know the chance that the child will reproduce with a carrier of the recessive mutation. This fact may not be known, but disease frequency is known. We know that the disease is caused by the homozygous recessive genotype; we can use the Hardy–Weinberg principle to work backward from disease occurrence to the frequency of heterozygous recessive individuals.

Scope and theoretical considerations

The mathematics of population genetics were originally developed as part of the modern evolutionary synthesis. According to Beatty (1986), it defines the core of the modern synthesis.

According to Lewontin (1974), the theoretical task for population genetics is a process in two spaces: a "genotypic space" and a "phenotypic space". The challenge of a *complete* theory of population genetics is to provide a set of laws that predictably map a population of genotypes (G_1) to a phenotype space (P_1), where selection takes place, and another set of laws that map the resulting population (P_2) back to genotype space (G_2) where Mendelian genetics can predict the next generation of genotypes, thus completing the cycle. Even leaving aside for the moment the non-Mendelian aspects of molecular genetics, this is clearly a gargantuan task. Visualizing this transformation schematically:

$$G_1 \xrightarrow{T_1} P_1 \xrightarrow{T_2} P_2 \xrightarrow{T_3} G_2 \xrightarrow{T_4} G_1' \rightarrow \cdots$$

(adapted from Lewontin 1974, p. 12). XD

T_1 represents the genetic and epigenetic laws, the aspects of functional biology, or development, that transform a genotype into phenotype. We will refer to this as the "genotype-phenotype map". T_2 is the transformation due to natural selection, T_3 are epigenetic relations that predict genotypes based on the selected phenotypes and finally T_4 the rules of Mendelian genetics.

In practice, there are two bodies of evolutionary theory that exist in parallel, traditional population genetics operating in the genotype space and the biometric theory used in plant and animal breeding, operating in phenotype space. The missing part is the mapping between the genotype and phenotype space. This leads to a "sleight of hand" (as Lewontin terms it) whereby variables in the equations of one domain, are considered parameters or *constants*, where, in a full-treatment they would be transformed themselves by the evolutionary process and are in reality *functions* of the state variables in the other domain. The "sleight of hand" is assuming that we know this mapping. Proceeding as if we do understand it is enough to analyze many cases of interest. For example, if the phenotype is almost one-to-one with genotype (sickle-cell disease) or the time-scale is sufficiently short, the "constants" can be treated as such; however, there are many situations where it is inaccurate.

The four processes

Natural selection

Natural selection is the process by which heritable traits that make it more likely for an organism to survive and successfully reproduce become more common in a population over successive generations.

The natural genetic variation within a population of organisms means that some individuals will survive more successfully than others in their current environment. Factors which affect reproductive success are also important, an issue which Charles Darwin developed in his ideas on sexual selection.

Natural selection acts on the phenotype, or the observable characteristics of an organism, but the genetic (heritable) basis of any phenotype which gives a reproductive advantage will become more common in a population (see allele frequency). Over time, this process can result in adaptations that specialize organisms for particular ecological niches and may eventually result in the emergence of new species.

Natural selection is one of the cornerstones of modern biology. The term was introduced by Darwin in his groundbreaking 1859 book *On the Origin of Species*,[4] in which natural selection was described by analogy to artificial selection, a process by which animals and plants with traits considered desirable by human breeders are systematically favored for reproduction. The concept of natural selection was originally developed in the absence of a valid theory of heredity; at the time of Darwin's writing, nothing was known of modern genetics. The union of traditional Darwinian evolution with subsequent discoveries in classical and molecular genetics is termed the *modern evolutionary synthesis*. Natural selection remains the primary explanation for adaptive evolution.

Genetic drift

Genetic drift is the change in the relative frequency in which a gene variant (allele) occurs in a population due to random sampling and chance. That is, the alleles in the offspring in the population are a random sample of those in the parents. And chance has a role in determining whether a given individual survives and reproduces. A population's allele frequency is the fraction or percentage of its gene copies compared to the total number of gene alleles that share a particular form.[5]

Genetic drift is an important evolutionary process which leads to changes in allele frequencies over time. It may cause gene variants to disappear completely, and thereby reduce genetic variability. In contrast to natural selection, which makes gene variants more common or less common depending on their reproductive success,[6] the changes due to genetic drift are not driven by environmental or adaptive pressures, and may be beneficial, neutral, or

detrimental to reproductive success.

The effect of genetic drift is larger in small populations, and smaller in large populations. Vigorous debates wage among scientists over the relative importance of genetic drift compared with natural selection. Ronald Fisher held the view that genetic drift plays at the most a minor role in evolution, and this remained the dominant view for several decades. In 1968 Motoo Kimura rekindled the debate with his neutral theory of molecular evolution which claims that most of the changes in the genetic material are caused by genetic drift.[7]

Mutation

Mutations are changes in the DNA sequence of a cell's genome and are caused by radiation, viruses, transposons and mutagenic chemicals, as well as errors that occur during meiosis or DNA replication.[8] [9] [10] Errors are introduced particularly often in the process of DNA replication, in the polymerization of the second strand. These errors can also be induced by the organism itself, by cellular processes such as hypermutation.

Mutations can have an impact on the phenotype of an organism, especially if they occur within the protein coding sequence of a gene. Error rates are usually very low (1 error in every 10 million–100 million bases) due to the "proofreading" ability of DNA polymerases.[11] [12] Without proofreading, error rates are a thousand-fold higher. Chemical damage to DNA occurs naturally as well, and cells use DNA repair mechanisms to repair mismatches and breaks in DNA. Nevertheless, the repair sometimes fails to return the DNA to its original sequence.

In organisms that use chromosomal crossover to exchange DNA and recombine genes, errors in alignment during meiosis can also cause mutations.[13] Errors in crossover are especially likely when similar sequences cause partner chromosomes to adopt a mistaken alignment; this makes some regions in genomes more prone to mutating in this way. These errors create large structural changes in DNA sequence—duplications, inversions or deletions of entire regions, or the accidental exchanging of whole parts between different chromosomes (called translocation).

Mutation can result in several different types of change in DNA sequences; these can either have no effect, alter the product of a gene, or prevent the gene from functioning. Studies in the fly *Drosophila melanogaster* suggest that if a mutation changes a protein produced by a gene, this will probably be harmful, with about 70 percent of these mutations having damaging effects, and the remainder being either neutral or weakly beneficial.[14] Due to the damaging effects that mutations can have on cells, organisms have evolved mechanisms such as DNA repair to remove mutations.[8] Therefore, the optimal mutation rate for a species is a trade-off between costs of a high mutation rate, such as deleterious mutations, and the metabolic costs of maintaining systems to reduce the mutation rate, such as DNA repair enzymes.[15] Viruses that use RNA as their genetic material have rapid mutation rates,[16] which can be an advantage since these viruses will evolve constantly and rapidly, and thus evade the defensive responses of e.g. the human immune system.[17]

Mutations can involve large sections of DNA becoming duplicated, usually through genetic recombination.[18] These duplications are a major source of raw material for evolving new genes, with tens to hundreds of genes duplicated in animal genomes every million years.[19] Most genes belong to larger families of genes of shared ancestry.[20] Novel genes are produced by several methods, commonly through the duplication and mutation of an ancestral gene, or by recombining parts of different genes to form new combinations with new functions.[21] [22]

Here, domains act as modules, each with a particular and independent function, that can be mixed together to produce genes encoding new proteins with novel properties.[23] For example, the human eye uses four genes to make structures that sense light: three for color vision and one for night vision; all four arose from a single ancestral gene.[24] Another advantage of duplicating a gene (or even an entire genome) is that this increases redundancy; this allows one gene in the pair to acquire a new function while the other copy performs the original function.[25] [26] Other types of mutation occasionally create new genes from previously noncoding DNA.[27] [28]

Gene flow

Gene flow is the exchange of genes between populations, which are usually of the same species.[29] Examples of gene flow within a species include the migration and then breeding of organisms, or the exchange of pollen. Gene transfer between species includes the formation of hybrid organisms and horizontal gene transfer.

Migration into or out of a population can change allele frequencies, as well as introducing genetic variation into a population. Immigration may add new genetic material to the established gene pool of a population. Conversely, emigration may remove genetic material. As barriers to reproduction between two diverging populations are required for the populations to become new species, gene flow may slow this process by spreading genetic differences between the populations. Gene flow is hindered by mountain ranges, oceans and deserts or even man-made structures such as the Great Wall of China, which has hindered the flow of plant genes.[30]

Depending on how far two species have diverged since their most recent common ancestor, it may still be possible for them to produce offspring, as with horses and donkeys mating to produce mules.[31] Such hybrids are generally infertile, due to the two different sets of chromosomes being unable to pair up during meiosis. In this case, closely related species may regularly interbreed, but hybrids will be selected against and the species will remain distinct. However, viable hybrids are occasionally formed and these new species can either have properties intermediate between their parent species, or possess a totally new phenotype.[32] The importance of hybridization in creating new species of animals is unclear, although cases have been seen in many types of animals,[33] with the gray tree frog being a particularly well-studied example.[34]

Hybridization is, however, an important means of speciation in plants, since polyploidy (having more than two copies of each chromosome) is tolerated in plants more readily than in animals.[35] [36] Polyploidy is important in hybrids as it allows reproduction, with the two different sets of chromosomes each being able to pair with an identical partner during meiosis.[37] Polyploids also have more genetic diversity, which allows them to avoid inbreeding depression in small populations.[38]

Horizontal gene transfer is the transfer of genetic material from one organism to another organism that is not its offspring; this is most common among bacteria.[39] In medicine, this contributes to the spread of antibiotic resistance, as when one bacteria acquires resistance genes it can rapidly transfer them to other species.[40] Horizontal transfer of genes from bacteria to eukaryotes such as the yeast *Saccharomyces cerevisiae* and the adzuki bean beetle *Callosobruchus chinensis* may also have occurred.[41] [42] An example of larger-scale transfers are the eukaryotic bdelloid rotifers, which appear to have received a range of genes from bacteria, fungi, and plants.[43] Viruses can also carry DNA between organisms, allowing transfer of genes even across biological domains.[44] Large-scale gene transfer has also occurred between the ancestors of eukaryotic cells and prokaryotes, during the acquisition of chloroplasts and mitochondria.[45]

Gene flow is the transfer of alleles from one population to another.

Migration into or out of a population may be responsible for a marked change in allele frequencies. Immigration may also result in the addition of new genetic variants to the established gene pool of a particular species or population.

There are a number of factors that affect the rate of gene flow between different populations. One of the most significant factors is mobility, as greater mobility of an individual tends to give it greater migratory potential. Animals tend to be more mobile than plants, although pollen and seeds may be carried great distances by animals or wind.

Maintained gene flow between two populations can also lead to a combination of the two gene pools, reducing the genetic variation between the two groups. It is for this reason that gene flow strongly acts against speciation, by recombining the gene pools of the groups, and thus, repairing the developing differences in genetic variation that would have led to full speciation and creation of daughter species.

For example, if a species of grass grows on both sides of a highway, pollen is likely to be transported from one side to the other and vice versa. If this pollen is able to fertilise the plant where it ends up and produce viable offspring,

then the alleles in the pollen have effectively been able to move from the population on one side of the highway to the other.

Genetic structure

Because of physical barriers to migration, along with limited vagility, and natal philopatry, natural populations are rarely panmictic (Buston *et al.*, 2007). There is usually a geographic range within which individuals are more closely related to one another than those randomly selected from the general population. This is described as the extent to which a population is genetically structured (Repaci *et al.*, 2007).

Microbial population genetics

Microbial population genetics is a rapidly advancing field of investigation with relevance to many other theoretical and applied areas of scientific investigations. The population genetics of microorganisms lays the foundations for tracking the origin and evolution of antibiotic resistance and deadly infectious pathogens. Population genetics of microorganisms is also an essential factor for devising strategies for the conservation and better utilization of beneficial microbes (Xu, 2010).

History

Biston betularia f. typica is the white-bodied form of the peppered moth.

Biston betularia f. carbonaria is the black-bodied form of the peppered moth.

Population genetics

The Mendelian and biometrician models were eventually reconciled, when *population genetics* was developed. A key step was the work of the British biologist and statistician R.A. Fisher. In a series of papers starting in 1918 and culminating in his 1930 book *The Genetical Theory of Natural Selection*, Fisher showed that the continuous variation measured by the biometricians could be produced by the combined action of many discrete genes, and that natural selection could change gene frequencies in a population, resulting in evolution. In a series of papers beginning in 1924, another British geneticist, J.B.S. Haldane, applied statistical analysis to real-world examples of natural selection, such as the evolution of industrial melanism in peppered moths, and showed that natural selection worked at an even faster rate than Fisher assumed.[46] [47]

The American biologist Sewall Wright, who had a background in animal breeding experiments, focused on combinations of interacting genes, and the effects of inbreeding on small, relatively isolated populations that exhibited genetic drift. In 1932, Wright introduced the concept of an adaptive landscape and argued that genetic drift and inbreeding could drive a small, isolated sub-population away from an adaptive peak, allowing natural selection to drive it towards different adaptive peaks. Fisher and Wright had some fundamental disagreements and a

controversy about the relative roles of selection and drift continued for much of the century between the Americans and the British. The Frenchman Gustave Malécot was also important early in the development of the discipline.

The work of Fisher, Haldane and Wright founded the discipline of *population genetics*. This integrated natural selection with Mendelian genetics, which was the critical first step in developing a unified theory of how evolution worked.[46] [47]

John Maynard Smith was Haldane's pupil, whilst W.D. Hamilton was heavily influenced by the writings of Fisher. The American George R. Price worked with both Hamilton and Maynard Smith. American Richard Lewontin and Japanese Motoo Kimura were heavily influenced by Wright.

Modern evolutionary synthesis

In the first few decades of the 20th century, most field naturalists continued to believe that Lamarckian and orthogenic mechanisms of evolution provided the best explanation for the complexity they observed in the living world. However, as the field of genetics continued to develop, those views became less tenable.[48] Theodosius Dobzhansky, a postdoctoral worker in T. H. Morgan's lab, had been influenced by the work on genetic diversity by Russian geneticists such as Sergei Chetverikov. He helped to bridge the divide between the foundations of microevolution developed by the population geneticists and the patterns of macroevolution observed by field biologists, with his 1937 book *Genetics and the Origin of Species*.

Dobzhansky examined the genetic diversity of wild populations and showed that, contrary to the assumptions of the population geneticists, these populations had large amounts of genetic diversity, with marked differences between sub-populations. The book also took the highly mathematical work of the population geneticists and put it into a more accessible form. In Great Britain E.B. Ford, the pioneer of ecological genetics, continued throughout the 1930s and 1940s to demonstrate the power of selection due to ecological factors including the ability to maintain genetic diversity through genetic polymorphisms such as human blood types. Ford's work would contribute to a shift in emphasis during the course of the modern synthesis towards natural selection over genetic drift.[46] [47] [49] [50]

See also

- Coalescent theory
- Dual inheritance theory
- Ecological genetics
- Evolutionarily Significant Unit
- Ewens's sampling formula
- Fitness landscape
- Founder effect
- Genetic diversity
- Genetic drift
- Genetic erosion
- Genetic pollution
- Gene pool
- Genotype-phenotype distinction
- Habitat fragmentation
- Hardy-Weinberg principle
- Microevolution
- Molecular evolution
- Muller's ratchet
- Mutational meltdown
- Neutral theory of molecular evolution

- Population bottleneck
- Quantitative genetics
- Reproductive compensation
- Selection
- Small population size
- Viral quasispecies

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External links

- Yale University (http://alfred.med.yale.edu/alfred/)
- EHSTRAFD.org - Earth Human STR Allele Frequencies Database (http://www.ehstrafd.org)
- History of population genetics (http://www.esp.org/books/sturt/history/contents/sturt-history-ch-17.pdf)
- National Geographic: Atlas of the Human Journey (https://www5.nationalgeographic.com/genographic/atlas.html) (Haplogroup-based human migration maps)
- Monash Virtual Laboratory (http://vlab.infotech.monash.edu.au/simulations/cellular-automata/population-genetics/) - Simulations of habitat fragmentation and population genetics online at Monash University's Virtual Laboratory.

Gene flow

In population genetics, **gene flow** (also known as **gene migration**) is the transfer of alleles of genes from one population to another.

Migration into or out of a population may be responsible for a marked change in allele frequencies (the proportion of members carrying a particular variant of a gene). Immigration may also result in the addition of new genetic variants to the established gene pool of a particular species or population.

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Barrier to gene flow

Physical barriers to gene flow are usually, but not always, natural. They may include impassable mountain ranges, oceans, or vast deserts. In some cases, they can be artificial, man-made barriers, such as the Great Wall of China, which has hindered the gene flow of native plant populations[1] . Samples of the same species which grow on either side have been shown to have developed genetic differences, because there is little to no gene flow to provide recombination of the gene pools.

Barriers to gene flow need not always be physical. Species can live in the same environment, yet show very limited gene flow due to limited hybridization or hybridization yielding unfit hybrids.

Gene flow in humans

Gene flow has been observed in humans. For example, in the United States, gene flow was observed between a white European population and a black West African population, which were recently brought together. In West Africa, where malaria is prevalent, the Duffy antigen provides some resistance to the disease, and this allele is thus present in nearly all of the West African population. In contrast, Europeans have either the allele $\mathbf{Fy^a}$ or $\mathbf{Fy^b}$, because malaria is almost non-existent. By measuring the frequencies of the West African and European groups, scientists found that the allele frequencies became mixed in each population because of movement of individuals. It was also found that this gene flow between European and West African groups is much greater in the Northern U.S. than in the South.

Gene flow between species

Gene flow can occur between species, either through hybridization or gene transfer from bacteria or virus to new hosts.

Gene transfer, defined as the movement of genetic material across species boundaries, which includes horizontal gene transfer, antigenic shift, and reassortment is sometimes an important source of genetic variation. Viruses can transfer genes between species [2]. Bacteria can incorporate genes from other dead bacteria, exchange genes with living bacteria, and can exchange plasmids across species boundaries [3]. "Sequence comparisons suggest recent horizontal transfer of many genes among diverse species including across the boundaries of phylogenetic "domains". Thus determining the phylogenetic history of a species can not be done conclusively by determining evolutionary trees for single genes." [4]

Biologist Gogarten suggests "the original metaphor of a tree no longer fits the data from recent genome research". Biologists [should] instead use the metaphor of a mosaic to describe the different histories combined in individual genomes and use the metaphor of an intertwined net to visualize the rich exchange and cooperative effects of horizontal gene transfer. [5]

"Using single genes as phylogenetic markers, it is difficult to trace organismal phylogeny in the presence of HGT [horizontal gene transfer]. Combining the simple coalescence model of cladogenesis with rare HGT [horizontal gene transfer] events suggest there was no single last common ancestor that contained all of the genes ancestral to those shared among the three domains of life. Each contemporary molecule has its own history and traces back to an individual molecule cenancestor. However, these molecular ancestors were likely to be present in different organisms at different times." [6]

Genetic pollution

Purebred, naturally-evolved, region-specific, wild species can be threatened with extinction in a big way[7] through the process of genetic pollution, potentially causing uncontrolled hybridization, introgression and genetic swamping. These processes can lead to homogenization or replacement of local genotypes as a result of either a numerical and/or fitness advantage of introduced plant or animal[8] . Nonnative species can bring about a form of extinction of native plants and animals by hybridization and introgression either through purposeful introduction by humans or through habitat modification, bringing previously isolated species into contact. These phenomena can be especially detrimental for rare species coming into contact with more abundant ones. Interbreeding between the species can cause a 'swamping' of the rarer species' gene pool, creating hybrids that drive the originally purebred native stock to complete extinction. The extent of this facet of gene flow is not always apparent from morphological (outward appearance) observations alone. Some degree of gene flow may be due to normal, evolutionarily constructive processes, and all constellations of genes and genotypes cannot be preserved. That being said, hybridization with or without introgression may threaten a rare species' existence nonetheless.[9] [10] .

Models of gene flow

Models of gene flow can be derived from population genetics, e.g. Sewall Wright's neighborhood model, Wright's island model and the stepping stone model.

Gene flow mitigation

When cultivating genetically modified (GM) plants or livestock, it becomes necessary to prevent "genetic pollution" i.e. their genetic modification from reaching other conventionally hybridized or wild native plant and animal populations by using gene flow mitigation usually through unintentional cross pollination and crossbreeding. Reasons to limit gene flow may include biosafety or agricultural co-existence, in which GM and non-GM cropping systems work side by side.

Scientists in several large research programmes are investigating methods of limiting gene flow in plants. Among these programmes are Transcontainer, which investigates methods for biocontainment, SIGMEA, which focuses on the biosafety of genetically modified plants, and Co-Extra, which studies the co-existence of GM and non-GM product chains.

Generally, there are three approaches to gene flow mitigation: keeping the genetic modification out of the pollen, preventing the formation of pollen, and keeping the pollen inside the flower.

- The first approach requires transplastomic plants. In transplastomic plants, the modified DNA is not situated in the cell's nucleus but is present in plastids, which are cellular compartments outside the nucleus. An example for plastids are chloroplasts, in which photosynthesis occurs. In some plants, the pollen does not contain plastids and, consequently, any modification located in plastids cannot be transmitted by the pollen.
- The second approach relies on male sterile plants. Male sterile plants are unable to produce functioning flowers and therefore cannot release viable pollen. Cytoplasmic male sterile plants are known to produce higher yields. Therefore, researchers are trying to introduce this trait to genetically modified crops.
- The third approach works by preventing the flowers from opening. This trait is called cleistogamy and occurs naturally in some plants. Cleistogamous plants produce flowers which either open only partly or not at all. However, it remains unclear how reliable cleistogamy is for gene flow mitigation: a Co-Extra research project on rapeseed investigating the matter has published preliminary results which cast doubt on the attainment of a high degree of reliability.

See also

- Biological dispersal
- Genetic pollution
- Genetic erosion
- Genetic admixture

External links

- Co-Extra research on gene flow mitigation [11]
- Transcontainer research on biocontainment [12]
- SIGMEA research on the biosafety of GMOs: http://sigmea.dyndns.org [13]

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Speciation

Speciation is the evolutionary process by which new biological species arise. The biologist Orator F. Cook seems to have been the first to coin the term 'speciation' for the splitting of lineages or 'cladogenesis,' as opposed to 'anagenesis' or 'phyletic evolution' occurring within lineages.[1] [2] Whether genetic drift is a minor or major contributor to speciation is the subject of much ongoing discussion. There are four geographic modes of speciation in nature, based on the extent to which speciating populations are geographically isolated from one another: allopatric, peripatric, parapatric, and sympatric. Speciation may also be induced artificially, through animal husbandry or laboratory experiments. Observed examples of each kind of speciation are provided throughout.[3]

Natural speciation

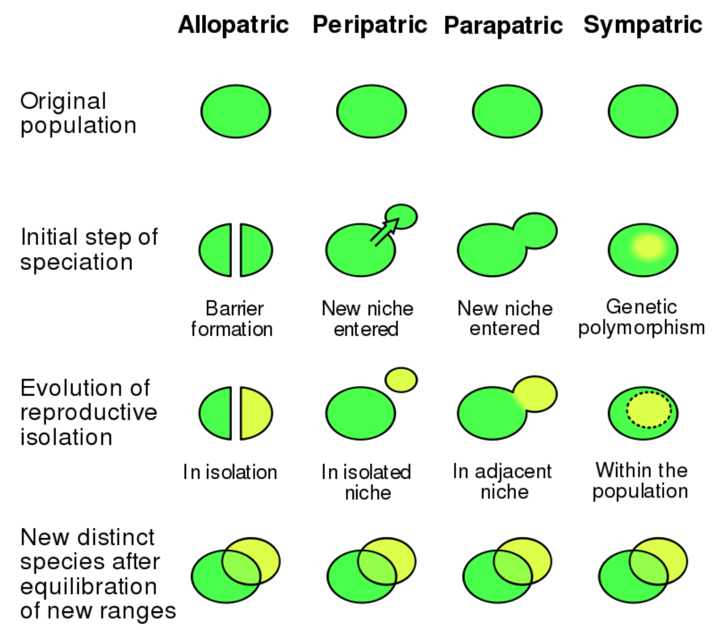
All forms of natural speciation have taken place over the course of evolution; however it still remains a subject of debate as to the relative importance of each mechanism in driving biodiversity.[4]

The three-spined stickleback (*Gasterosteus aculeatus*)

One example of natural speciation is the diversity of the three-spined stickleback, a marine fish that, after the last ice age, has undergone speciation into new freshwater colonies in isolated lakes and streams. Over an estimated 10,000 generations, the sticklebacks show structural differences that are greater than those seen between different genera of fish including variations in fins, changes in the number or size of their bony plates, variable jaw structure, and color differences.[5]

There is debate as to the rate at which speciation events occur over geologic time. While some evolutionary biologists claim that speciation events have remained relatively constant over time, some palaeontologists such as Niles Eldredge and Stephen Jay Gould have argued that species usually remain unchanged over long stretches of time, and that speciation occurs only over relatively brief intervals, a view known as *punctuated equilibrium*.

Allopatric



Comparison of allopatric, peripatric, parapatric and sympatric speciation.

During allopatric speciation, a population splits into two geographically isolated allopatric populations (for example, by habitat fragmentation due to geographical change such as mountain building or social change such as emigration). The isolated populations then undergo genotypic and/or phenotypic divergence as they (a) become subjected to dissimilar selective pressures or (b) they independently undergo genetic drift. When the populations come back into contact, they have evolved such that they are reproductively isolated and are no longer capable of exchanging genes.

Observed instances

Island genetics, the tendency of small, isolated genetic pools to produce unusual traits, has been observed in many circumstances, including insular dwarfism and the radical changes among certain famous island chains, for example on Komodo. The Galápagos islands are particularly famous for their influence on Charles Darwin. During his five weeks there he heard that Galápagos tortoises could be identified by island, and noticed that Mockingbirds differed from one island to another, but it was only nine months later that he reflected that such facts could show that species were changeable. When he returned to England, his speculation on evolution deepened after experts informed him that these were separate species, not just varieties, and famously that other differing Galápagos birds were all species of finches. Though the finches were less important for Darwin, more recent research has shown the birds now known as Darwin's finches to be a classic case of adaptive evolutionary radiation.[6]

Peripatric

In peripatric speciation, new species are formed in isolated, small peripheral populations that are prevented from exchanging genes with the main population. It is related to the concept of a founder effect, since small populations often undergo bottlenecks. Genetic drift is often proposed to play a significant role in peripatric speciation.

Observed instances

- Mayr bird fauna
- The Australian bird *Petroica multicolor*
- Reproductive isolation occurs in populations of *Drosophila* subject to population bottlenecking

The London Underground mosquito is a variant of the mosquito *Culex pipiens* that entered in the London Underground in the nineteenth century. Evidence for its speciation include genetic divergence, behavioral differences, and difficulty in mating.[7]

Parapatric

In parapatric speciation, the zones of two diverging populations are separate but do overlap. There is only partial separation afforded by geography, so individuals of each species may come in contact or cross the barrier from time to time, but reduced fitness of the heterozygote leads to selection for behaviours or mechanisms that prevent breeding between the two species.

Ecologists refer to parapatric and peripatric speciation in terms of ecological niches. A niche must be available in order for a new species to be successful.

Observed instances

- Ring species
  - The *Larus* gulls form a ring species around the North Pole.
  - The *Ensatina* salamanders, which form a ring round the Central Valley in California.
  - The Greenish Warbler (*Phylloscopus trochiloides*), around the Himalayas.
- the grass *Anthoxanthum* has been known to undergo parapatric speciation in such cases as mine contamination of an area.

Sympatric

In sympatric speciation, species diverge while inhabiting the same place. Often cited examples of sympatric speciation are found in insects that become dependent on different host plants in the same area. However, the existence of sympatric speciation as a mechanism of speciation is still hotly contested. People have argued that the evidences of sympatric speciation are in fact examples of micro-allopatric, or heteropatric speciation. The most widely accepted example of sympatric speciation is that of the cichlids of Lake Nabugabo in East Africa, which is thought to be due to **sexual selection**. Sympatric speciation refers to the formation of two or more descendant species from a single ancestral species all occupying the same geographic location.

Until recently, there has a been a dearth of hard evidence that supports this form of speciation, with a general feeling that interbreeding would soon eliminate any genetic differences that might appear. But there has been at least one recent study that suggests that sympatric speciation has occurred in Tennessee cave salamanders.[8]

The three-spined sticklebacks, freshwater fishes, that have been studied by Dolph Schluter (who received his Ph.D. for his work on Darwin's finches with Peter Grant) and his current colleagues in British Columbia, were once thought to provide an intriguing example best explained by sympatric speciation. Schluter and colleagues have found:

- Two different species of three-spined sticklebacks in each of five different lakes.
  - a large benthic species with a large mouth that feeds on large prey in the littoral zone
  - a smaller limnetic species — with a smaller mouth — that feeds on the small plankton in open water.
- DNA analysis indicates that each lake was colonized independently, presumably by a marine ancestor, after the last ice age.
- DNA analysis also shows that the two species in each lake are more closely related to each other than they are to any of the species in the other lakes.
- Nevertheless, the two species in each lake are reproductively isolated; neither mates with the other.
- However, aquarium tests showed that
  - the benthic species from one lake will spawn with the benthic species from the other lakes and
  - likewise the limnetic species from the different lakes will spawn with each other.
  - These benthic and limnetic species even display their mating preferences when presented with sticklebacks from Japanese lakes; that is, a Canadian benthic prefers a Japanese benthic over its close limnetic cousin from its own lake.

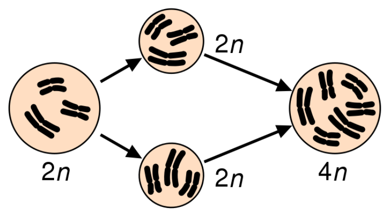
- Their conclusion: in each lake, what began as a single population faced such competition for limited resources that
  - disruptive selection — competition favoring fishes at either extreme of body size and mouth size over those nearer the mean — coupled with
  - assortative mating — each size preferred mates like it - favored a divergence into two subpopulations exploiting different food in different parts of the lake.
  - The fact that this pattern of speciation occurred the same way on three separate occasions suggests strongly that ecological factors in a sympatric population can cause speciation.

However, the DNA evidence cited above is from mitochondrial DNA (mtDNA), which can often move easily between closely related species ("introgression") when they hybridize. A more recent study,[9] using genetic markers from the nuclear genome, shows that limnetic forms in different lakes are more closely related to each other (and to marine lineages) than to benthic forms in the same lake. The threespine stickleback is now considered an example of "double invasion" (a form of allopatric speciation) in which repeated invasions of marine forms have subsequently differentiated into benthic and limnetic forms. The threesspine stickleback provides an example of how molecular biogeographic studies that rely solely on mtDNA can be misleading, and that consideration of the genealogical history of alleles from multiple unlinked markers (i.e. nuclear genes) is necessary to infer speciation histories.

Sympatric speciation driven by ecological factors may also account for the extraordinary diversity of crustaceans living in the depths of Siberia's Lake Baikal.

Speciation via polyploidization

Polyploidy is a mechanism often attributed to causing some speciation events in sympatry. Not all polyploids are reproductively isolated from their parental plants, so an increase in chromosome number may not result in the complete cessation of gene flow between the incipient polyploids and their parental diploids (see also hybrid speciation).



Speciation via polyploidy: A diploid cell undergoes failed meiosis, producing diploid gametes, which self-fertilize to produce a tetraploid zygote.

Polyploidy is observed in many species of both plants and animals. In fact, it has been proposed that all of the existing plants and most of the animals are polyploids or have undergone an event of polyploidization in their evolutionary history. However, reproduction is often by parthenogenesis since polyploid animals are often sterile. Rare instances of polyploid mammals are known, but most often result in prenatal death.

Hawthorn fly

One example of evolution at work is the case of the hawthorn fly, *Rhagoletis pomonella*, also known as the apple maggot fly, which appears to be undergoing sympatric speciation.[10] Different populations of hawthorn fly feed on different fruits. A distinct population emerged in North America in the 19th century some time after apples, a non-native species, were introduced. This apple-feeding population normally feeds only on apples and not on the historically preferred fruit of hawthorns. The current hawthorn feeding population does not normally feed on apples. Some evidence, such as the fact that six out of thirteen allozyme loci are different, that hawthorn flies mature later in the season and take longer to mature than apple flies; and that there is little evidence of interbreeding (researchers have documented a 4-6% hybridization rate) suggests that sympatric speciation is occurring. The emergence of the new hawthorn fly is an example of evolution in progress.[11]

Speciation via hybrid formation

See Hybrid speciation section under the Genetics heading below.

Reinforcement (Wallace effect)

Reinforcement is the process by which natural selection increases reproductive isolation.[12] It may occur after two populations of the same species are separated and then come back into contact. If their reproductive isolation was complete, then they will have already developed into two separate incompatible species. If their reproductive isolation is incomplete, then further mating between the populations will produce hybrids, which may or may not be fertile. If the hybrids are infertile, or fertile but less fit than their ancestors, then there will be no further reproductive isolation and speciation has essentially occurred (e.g., as in horses and donkeys.) The reasoning behind this is that if the parents of the hybrid offspring each have naturally selected traits for their own certain environments, the hybrid offspring will bear traits from both, therefore would not fit either ecological niche as well as the parents did. The low fitness of the hybrids would cause selection to favor assortative mating, which would control hybridization. This is sometimes called the Wallace effect after the evolutionary biologist Alfred Russel Wallace who suggested in the late 19th century that it might be an important factor in speciation.[13] If the hybrid offspring are more fit than their ancestors, then the populations will merge back into the same species within the area they are in contact.

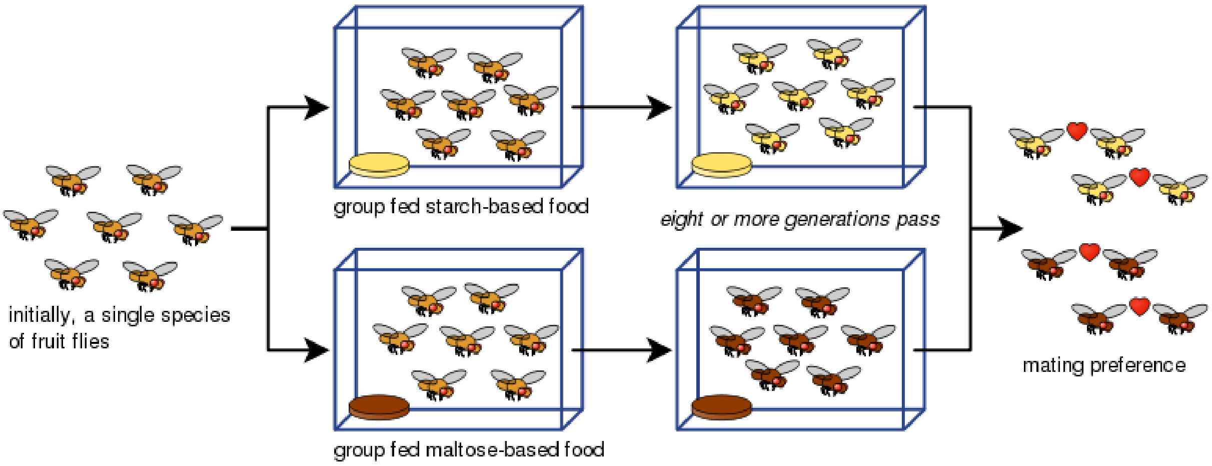
Reinforcement is required for both parapatric and sympatric speciation. Without reinforcement, the geographic area of contact between different forms of the same species, called their "hybrid zone," will not develop into a boundary between the different species. Hybrid zones are regions where diverged populations meet and interbreed. Hybrid offspring are very common in these regions, which are usually created by diverged species coming into secondary contact. Without reinforcement the two species would have uncontrollable inbreeding. Reinforcement may be induced in artificial selection experiments as described below.

Artificial speciation

New species have been created by domesticated animal husbandry, but the initial dates and methods of the initiation of such species are not clear. For example, domestic sheep were created by hybridisation, and no longer produce viable offspring with *Ovis orientalis*, one species from which they are descended.[14] Domestic cattle, on the other hand, can be considered the same species as several varieties of wild ox, gaur, yak, etc., as they readily produce fertile offspring with them.[15]

The best-documented creations of new species in the laboratory were performed in the late 1980s. William Rice and G.W. Salt bred fruit flies, *Drosophila melanogaster,* using a maze with three different choices of habitat such as light/dark and wet/dry. Each generation was placed into the maze, and the groups of flies that came out of two of the eight exits were set apart to breed with each other in their respective groups. After thirty-five generations, the two groups and their offspring were isolated reproductively because of their strong habitat preferences: they mated only within the areas they preferred, and so did not mate with flies that preferred the other areas.[16] The history of such attempts is described in Rice and Hostert (1993).[17]

Diane Dodd was also able to show how reproductive isolation can develop from mating preferences in *Drosophila pseudoobscura* fruit flies after only eight generations using different food types, starch and maltose.[18]



Dodd's experiment has been easy for many others to replicate, including with other kinds of fruit flies and foods.[19]

Genetics

Few speciation genes have been found. They usually involve the reinforcement process of late stages of speciation. In 2008 a speciation gene causing reproductive isolation was reported.[20] It causes hybrid sterility between related subspecies.

Hybrid speciation

Hybridization between two different species sometimes leads to a distinct phenotype. This phenotype can also be fitter than the parental lineage and as such natural selection may then favor these individuals. Eventually, if reproductive isolation is achieved, it may lead to a separate species. However, reproductive isolation between hybrids and their parents is particularly difficult to achieve and thus hybrid speciation is considered an extremely rare event. The Mariana Mallard is known to have arisen from hybrid speciation.

Hybridization without change in chromosome number is called homoploid hybrid speciation. It is considered very rare but has been shown in *Heliconius* butterflies [21] and sunflowers. Polyploid speciation, which involves changes in chromosome number, is a more common phenomenon, especially in plant species.

Gene transposition as a cause

Theodosius Dobzhansky, who studied fruit flies in the early days of genetic research in 1930s, speculated that parts of chromosomes that switch from one location to another might cause a species to split into two different species. He mapped out how it might be possible for sections of chromosomes to relocate themselves in a genome. Those mobile sections can cause sterility in inter-species hybrids, which can act as a speciation pressure. In theory, his idea was sound, but scientists long debated whether it actually happened in nature. Eventually a competing theory involving the gradual accumulation of mutations was shown to occur in nature so often that geneticists largely dismissed the moving gene hypothesis.[22]

However, 2006 research shows that jumping of a gene from one chromosome to another can contribute to the birth of new species.[23] This validates the reproductive isolation mechanism, a key component of speciation.[24]

Interspersed repeats

Interspersed repetitive DNA sequences function as isolating mechanisms. These repeats protect newly evolving gene sequences from being overwritten by gene conversion, due to the creation of non-homologies between otherwise homologous DNA sequences. The non-homologies create barriers to gene conversion. This barrier allows nascent novel genes to evolve without being overwritten by the progenitors of these genes. This uncoupling allows the evolution of new genes, both within gene families and also allelic forms of a gene. The importance is that this allows the splitting of a gene pool without requiring physical isolation of the organisms harboring those gene sequences.

Human speciation

Humans have genetic similarities with chimpanzees and gorillas, suggesting common ancestors. Analysis of genetic drift and recombination using a Markov model suggests humans and chimpanzees speciated apart 4.1 million years ago.[25]

See also

- Extinction
- Species problem
- Heteropatry
- Chronospecies
- Koinophilia

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External links

- *Observed Instances of Speciation* [27] from the Talk.Origins Frequently Asked Questions [28]
- Speciation [29], and
- Evidence for Speciation [30] from Understanding Evolution [31] by the University of California Museum of Paleontology
- Speciation [32] from John Hawks' Anthropology Weblog - paleoanthropology, genetics, and evolution [33]
- Speciation in the context of evolution [34]

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Natural selection

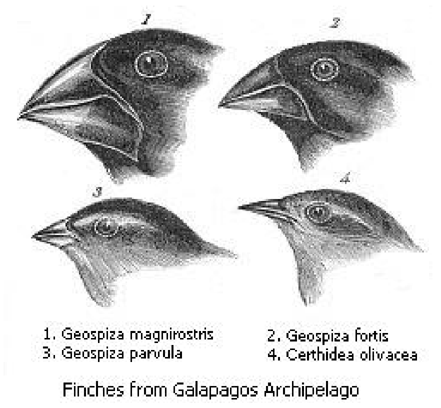
Natural selection is the process by which those heritable traits that make it more likely for an organism to survive and successfully reproduce become more common in a population over successive generations. It is a key mechanism of evolution.

The natural genetic variation within a population of organisms means that some individuals will survive and reproduce more successfully than others in their current environment. For example, the peppered moth exists in both light and dark colors in the United Kingdom, but during the industrial revolution many of the trees on which the moths rested became blackened by soot, giving the dark-colored moths an advantage in hiding from predators. This gave dark-colored moths a better chance of surviving to produce dark-colored offspring, and in just a few generations the majority of the moths were dark. Factors which affect reproductive success are also important, an issue which Charles Darwin developed in his ideas on sexual selection.

Natural selection acts on the phenotype, or the observable characteristics of an organism, but the genetic (heritable) basis of any phenotype which gives a reproductive advantage will become more common in a population (see allele frequency). Over time, this process can result in adaptations that specialize organisms for particular ecological niches and may eventually result in the emergence of new species. In other words, natural selection is an important process (though not the only process) by which evolution takes place within a population of organisms.

Natural selection is one of the cornerstones of modern biology. The term was introduced by Darwin in his influential 1859 book *On the Origin of Species*,[1] in which natural selection was described as analogous to artificial selection, a process by which animals and plants with traits considered desirable by human breeders are systematically favored for reproduction. The concept of natural selection was originally developed in the absence of a valid theory of heredity; at the time of Darwin's writing, nothing was known of modern genetics. The union of traditional Darwinian evolution with subsequent discoveries in classical and molecular genetics is termed the *modern evolutionary synthesis*. Natural selection remains the primary explanation for adaptive evolution.

General principles



Darwin's illustrations of beak variation in the finches of the Galápagos Islands, which hold 13 closely related species that differ most markedly in the shape of their beaks. The beak of each species is suited to its preferred food, suggesting that beak shapes evolved by natural selection.

Natural variation occurs among the individuals of any population of organisms. Many of these differences do not affect survival (such as differences in eye color in humans), but some differences may improve the chances of survival of a particular individual. A rabbit that runs faster than others may be more likely to escape from predators, and algae that are more efficient at extracting energy from sunlight will grow faster. Individuals that have better odds for survival also have better odds for reproduction.

If the traits that give these individuals a reproductive advantage are also heritable, that is, passed from parent to child, then there will be a slightly higher proportion of fast rabbits or efficient algae in the next generation. This is known as *differential reproduction*. Even if the reproductive advantage is very slight, over many generations any heritable advantage will become dominant in the population, due to exponential growth. In this way the natural environment of an organism "selects" for traits that confer a reproductive advantage, causing gradual changes or evolution of life. This effect was first described and named by Charles Darwin.

The concept of natural selection predates the understanding of genetics, which is the study of heredity. In modern times, it is understood that selection acts on an organism's phenotype, or observable characteristics, but it is the organism's genetic make-up or genotype that is inherited. The phenotype is the result of the genotype and the environment in which the organism lives (see Genotype-phenotype distinction).

This is the link between natural selection and genetics, as described in the modern evolutionary synthesis. Although a complete theory of evolution also requires an account of how genetic variation arises in the first place (such as by mutation and sexual reproduction) and includes other evolutionary mechanisms (such as gene flow), natural selection is still understood as a fundamental mechanism for evolution.

Nomenclature and usage

The term *natural selection* has slightly different definitions in different contexts. It is most often defined to operate on heritable traits, because these are the traits that directly participate in evolution. However, natural selection is "blind" in the sense that changes in phenotype (physical and behavioral characteristics) can give a reproductive advantage regardless of whether or not the trait is heritable (non heritable traits can be the result of environmental factors or the life experience of the organism).

Following Darwin's primary usage[1] the term is often used to refer to both the evolutionary consequence of blind selection and to its mechanisms.[2] [3] It is sometimes helpful to explicitly distinguish between selection's mechanisms and its effects; when this distinction is important, scientists define "natural selection" specifically as "those mechanisms that contribute to the selection of individuals that reproduce", without regard to whether the basis of the selection is heritable. This is sometimes referred to as "phenotypic natural selection".[4]

Traits that cause greater reproductive success of an organism are said to be selected for, whereas those that reduce success are selected against. Selection for a trait may also result in the selection of other correlated traits that do not themselves directly influence reproductive advantage. This may occur as a result of pleiotropy or gene linkage.[5]

Fitness

The concept of fitness is central to natural selection. Broadly, individuals which are more "fit" have better potential for survival, as in the well-known phrase "survival of the fittest". However, as with natural selection above, the precise meaning of the term is much more subtle, and Richard Dawkins manages in his later books to avoid it entirely. (He devotes a chapter of his book, *The Extended Phenotype*, to discussing the various senses in which the term is used). Modern evolutionary theory defines fitness not by how long an organism lives, but by how successful it is at reproducing. If an organism lives half as long as others of its species, but has twice as many offspring surviving to adulthood, its genes will become more common in the adult population of the next generation.

Though natural selection acts on individuals, the effects of chance mean that fitness can only really be defined "on average" for the individuals within a population. The fitness of a particular genotype corresponds to the average effect on all individuals with that genotype. Very low-fitness genotypes cause their bearers to have few or no offspring on average; examples include many human genetic disorders like cystic fibrosis.

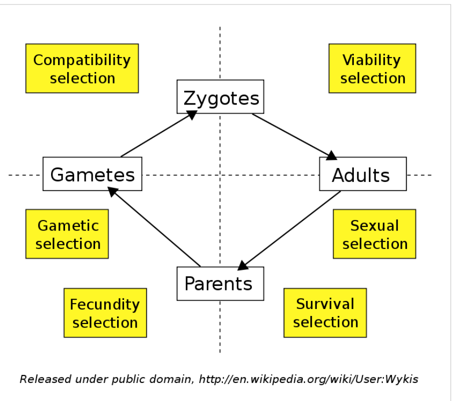
Since fitness is an averaged quantity, it is also possible that a favorable mutation arises in an individual that does not survive to adulthood for unrelated reasons. Fitness also depends crucially upon the environment. Conditions like sickle-cell anemia may have low fitness in the general human population, but because the sickle-cell trait confers immunity from malaria, it has high fitness value in populations which have high malaria infection rates.

Types of selection

Natural selection can act on any phenotypic trait, and selective pressure can be produced by any aspect of the environment, including sexual selection and competition with members of the same species. However, this does not imply that natural selection is always directional and results in adaptive evolution; natural selection often results in the maintenance of the status quo by eliminating less fit variants.

The unit of selection can be the individual or it can be another level within the hierarchy of biological organisation, such as genes, cells, and kin groups. There is still debate about whether natural selection acts at the level of groups or species to produce adaptations that benefit a larger, non-kin group. Selection at a different level such as the gene can result in an increase in fitness for that gene, while at the same time reducing the fitness of the individuals carrying that gene, in a process called intragenomic conflict. Overall, the combined effect of all selection pressures at various levels determines the overall fitness of an individual, and hence the outcome of natural selection.

Natural selection occurs at every life stage of an individual. An individual organism must survive until adulthood before it can reproduce, and selection of those that reach this stage is called *viability selection*. In many species, adults must compete with each other for mates via sexual selection, and success in this competition determines who will parent the next generation. When individuals can reproduce more than once, a longer survival in the reproductive phase increases the number of offspring, called *survival selection*.



The life cycle of a sexually reproducing organism. Various components of natural selection are indicated for each life stage.[6]

The fecundity of both females and males (for example, giant sperm in certain species of *Drosophila*)[7] can be limited via "fecundity selection". The viability of produced gametes can differ, while intragenomic conflicts such as meiotic drive between the haploid gametes can result in gametic or "genic selection". Finally, the union of some combinations of eggs and sperm might be more compatible than others; this is termed *compatibility selection*.

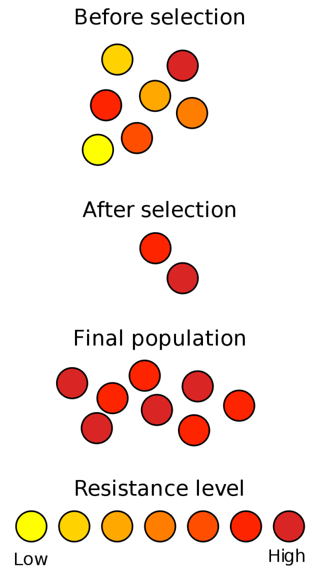
Sexual selection

It is useful to distinguish between "ecological selection" and "sexual selection". Ecological selection covers any mechanism of selection as a result of the environment (including relatives, e.g. kin selection, competition, and infanticide), while "sexual selection" refers specifically to competition for mates.[8]

Sexual selection can be *intrasexual*, as in cases of competition among individuals of the same sex in a population, or *intersexual*, as in cases where one sex controls reproductive access by choosing among a population of available mates. Most commonly, intrasexual selection involves male–male competition and intersexual selection involves female choice of suitable males, due to the generally greater investment of resources for a female than a male in a single offspring. However, some species exhibit sex-role reversed behavior in which it is males that are most selective in mate choice; the best-known examples of this pattern occur in some fishes of the family *Syngnathidae*, though likely examples have also been found in amphibian and bird species.[9]

Some features that are confined to one sex only of a particular species can be explained by selection exercised by the other sex in the choice of a mate, for example, the extravagant plumage of some male birds. Similarly, aggression between members of the same sex is sometimes associated with very distinctive features, such as the antlers of stags, which are used in combat with other stags. More generally, intrasexual selection is often associated with sexual dimorphism, including differences in body size between males and females of a species.[10]

Examples of natural selection



Resistance to antibiotics is increased though the survival of individuals which are immune to the effects of the antibiotic, whose offspring then inherit the resistance, creating a new population of resistant bacteria.

A well-known example of natural selection in action is the development of antibiotic resistance in microorganisms. Since the discovery of penicillin in 1928 by Alexander Fleming, antibiotics have been used to fight bacterial diseases. Natural populations of bacteria contain, among their vast numbers of individual members, considerable variation in their genetic material, primarily as the result of mutations. When exposed to antibiotics, most bacteria die quickly, but some may have mutations that make them slightly less susceptible. If the exposure to antibiotics is short, these individuals will survive the treatment. This selective elimination of maladapted individuals from a population is natural selection.

These surviving bacteria will then reproduce again, producing the next generation. Due to the elimination of the maladapted individuals in the past generation, this population contains more bacteria that have some resistance against the antibiotic. At the same time, new mutations occur, contributing new genetic variation to the existing genetic variation. Spontaneous mutations are very rare, and advantageous mutations are even rarer. However, populations of bacteria are large enough that a few individuals will have beneficial mutations. If a new mutation reduces their susceptibility to an antibiotic, these individuals are more likely to survive when next confronted with that antibiotic.

Given enough time, and repeated exposure to the antibiotic, a population of antibiotic-resistant bacteria will emerge. This new changed population of antibiotic-resistant bacteria is optimally adapted to the context it evolved in. At the same time, it is not necessarily optimally adapted any more to the old antibiotic free environment. The end result of natural selection is two populations that are both optimally adapted to their specific environment, while both perform substandard in the other environment.

The widespread use and misuse of antibiotics has resulted in increased microbial resistance to antibiotics in clinical use, to the point that the methicillin-resistant *Staphylococcus aureus* (MRSA) has been described as a "superbug" because of the threat it poses to health and its relative invulnerability to existing drugs.[11] Response strategies

typically include the use of different, stronger antibiotics; however, new strains of MRSA have recently emerged that are resistant even to these drugs.[12]

This is an example of what is known as an evolutionary arms race, in which bacteria continue to develop strains that are less susceptible to antibiotics, while medical researchers continue to develop new antibiotics that can kill them. A similar situation occurs with pesticide resistance in plants and insects. Arms races are not necessarily induced by man; a well-documented example involves the elaboration of the RNA interference pathway in plants as means of innate immunity against viruses.[13]

Evolution by means of natural selection

A prerequisite for natural selection to result in adaptive evolution, novel traits and speciation, is the presence of heritable genetic variation that results in fitness differences. Genetic variation is the result of mutations, recombinations and alterations in the karyotype (the number, shape, size and internal arrangement of the chromosomes). Any of these changes might have an effect that is highly advantageous or highly disadvantageous, but large effects are very rare. In the past, most changes in the genetic material were considered neutral or close to neutral because they occurred in noncoding DNA or resulted in a synonymous substitution. However, recent research suggests that many mutations in non-coding DNA do have slight deleterious effects.[14] [15] Although both mutation rates and average fitness effects of mutations are dependent on the organism, estimates from data in humans have found that a majority of mutations are slightly deleterious.[16]

The exuberant tail of the peacock is thought to be the result of sexual selection by females. This peacock is an albino; selection against albinos in nature is intense because they are easily spotted by predators or are unsuccessful in competition for mates.

By the definition of fitness, individuals with greater fitness are more likely to contribute offspring to the next generation, while individuals with lesser fitness are more likely to die early or fail to reproduce. As a result, alleles which on average result in greater fitness become more abundant in the next generation, while alleles which generally reduce fitness become rarer. If the selection forces remain the same for many generations, beneficial alleles become more and more abundant, until they dominate the population, while alleles with a lesser fitness disappear. In every generation, new mutations and recombinations arise spontaneously, producing a new spectrum of phenotypes. Therefore, each new generation will be enriched by the increasing abundance of alleles that contribute to those traits that were favored by selection, enhancing these traits over successive generations.

Some mutations occur in so-called regulatory genes. Changes in these can have large effects on the phenotype of the individual because they regulate the function of many other genes. Most, but not all, mutations in regulatory genes result in non-viable zygotes. Examples of nonlethal regulatory mutations occur in HOX genes in humans, which can result in a cervical rib[17] or polydactyly, an increase in the number of fingers or toes.[18] When such mutations result in a higher fitness, natural selection will favor these phenotypes and the novel trait will spread in the population.


X-ray of the left hand of a ten year old boy with polydactyly.

Established traits are not immutable; traits that have high fitness in one environmental context may be much less fit if environmental conditions change. In the absence of natural selection to preserve such a trait, it will become more variable and deteriorate over time, possibly resulting in a vestigial manifestation of the trait. In many circumstances, the apparently vestigial structure may retain a limited functionality, or may be co-opted for other advantageous traits in a phenomenon known as preadaptation. A famous example of a vestigial structure, the eye of the blind mole rat, is believed to retain function in photoperiod perception.[19]

Speciation

Speciation requires selective mating, which result in a reduced gene flow. Selective mating can be the result of, for example, a change in the physical environment (physical isolation by an extrinsic barrier), or by sexual selection resulting in assortative mating. Over time, these subgroups might diverge radically to become different species, either because of differences in selection pressures on the different subgroups, or because different mutations arise spontaneously in the different populations, or because of founder effects – some potentially beneficial alleles may, by chance, be present in only one or other of two subgroups when they first become separated. A lesser-known mechanism of speciation occurs via hybridization, well-documented in plants and occasionally observed in species-rich groups of animals such as cichlid fishes.[20] Such mechanisms of rapid speciation can reflect a mechanism of evolutionary change known as punctuated equilibrium, which suggests that evolutionary change and particularly speciation typically happens quickly after interrupting long periods of stasis.

Genetic changes within groups result in increasing incompatibility between the genomes of the two subgroups, thus reducing gene flow between the groups. Gene flow will effectively cease when the distinctive mutations characterizing each subgroup become fixed. As few as two mutations can result in speciation: if each mutation has a neutral or positive effect on fitness when they occur separately, but a negative effect when they occur together, then fixation of these genes in the respective subgroups will lead to two reproductively isolated populations. According to the biological species concept, these will be two different species.

Historical development

Pre-Darwinian theories

The modern theory of natural selection derives from the work of Charles Darwin in the nineteenth century.

Several ancient philosophers expressed the idea that nature produces a huge variety of creatures, apparently randomly, and that only those creatures survive that manage to provide for themselves and reproduce successfully; well-known examples include Empedocles[21] and his intellectual successor, Lucretius,[22] while related ideas were later refined by Aristotle.[23] The struggle for existence was later described by Al-Jahiz, who argued that environmental factors influence animals to develop new characteristics to ensure survival.[24] [25] [26] Abu Rayhan Biruni described the idea of artificial selection and argued that nature works in much the same way.[27] Similar ideas were later expressed by Nasir al-Din Tusi[28] and Ibn Khaldun.[29] [30] Such classical arguments were reintroduced in the 18th century by Pierre Louis Maupertuis[31] and others, including Charles Darwin's grandfather Erasmus Darwin. While these forerunners had an influence on Darwinism, they later had little influence on the trajectory of evolutionary thought after Charles Darwin.

Until the early 19th century, the prevailing view in Western societies was that differences between individuals of a species were uninteresting departures from their Platonic idealism (or typus) of created kinds. However, the theory of uniformitarianism in geology promoted the idea that simple, weak forces could act continuously over long periods of time to produce radical changes in the Earth's landscape. The success of this theory raised awareness of the vast scale of geological time and made plausible the idea that tiny, virtually imperceptible changes in successive generations could produce consequences on the scale of differences between species. Early 19th century evolutionists such as Jean Baptiste Lamarck suggested the inheritance of acquired characteristics as a mechanism for evolutionary change; adaptive traits acquired by an organism during its lifetime could be inherited by that organism's progeny, eventually causing transmutation of species.[32] This theory has come to be known as Lamarckism and was an influence on the anti-genetic ideas of the Stalinist Soviet biologist Trofim Lysenko.[33]

Darwin's theory

In 1859, Charles Darwin set out his theory of evolution by natural selection as an explanation for adaptation and speciation. He defined natural selection as the "principle by which each slight variation [of a trait], if useful, is preserved".[34] The concept was simple but powerful: individuals best adapted to their environments are more likely to survive and reproduce. As long as there is some variation between them, there will be an inevitable selection of individuals with the most advantageous variations. If the variations are inherited, then differential reproductive success will lead to a progressive evolution of particular populations of a species, and populations that evolve to be sufficiently different eventually become different species.[35]

Darwin's ideas were inspired by the observations that he had made on the *Beagle* voyage, and by the work of two political economists. The first was the Reverend Thomas Malthus, who in *An Essay on the Principle of Population*, noted that population (if unchecked) increases exponentially whereas the food supply grows only arithmetically; thus inevitable limitations of resources would have demographic implications, leading to a "struggle for existence" as a divinely ordained law "in order to rouse man into action, and form his mind to reason" for the greater good despite the "partial evil" limiting population.[36] The second was Adam Smith who, in *The Wealth of Nations*, identified a regulating mechanism in free markets, which he referred to as the "invisible hand", which suggests that prices

self-adjust according to supplies and demand.[37] When Darwin read Malthus in 1838 he was already primed by his work as a naturalist to appreciate the "struggle for existence" in nature and it struck him that as population outgrew resources, "favourable variations would tend to be preserved, and unfavourable ones to be destroyed. The result of this would be the formation of new species."[38]

Once he had his theory "by which to work", Darwin was meticulous about gathering and refining evidence as his "prime hobby" before making his idea public. He was in the process of writing his "big book" to present his researches when the naturalist Alfred Russel Wallace independently conceived of the principle and described it in an essay he sent to Darwin to forward to Charles Lyell. Lyell and Joseph Dalton Hooker decided (without Wallace's knowledge) to present his essay together with unpublished writings which Darwin had sent to fellow naturalists, and *On the Tendency of Species to form Varieties; and on the Perpetuation of Varieties and Species by Natural Means of Selection* was read to the Linnean Society announcing co-discovery of the principle in July 1858.[39] Darwin published a detailed account of his evidence and conclusions in *On the Origin of Species* in 1859. In the 3rd edition of 1861 Darwin acknowledged that others — notably William Charles Wells in 1813, and Patrick Matthew in 1831 — had proposed similar ideas, but had neither developed them nor presented them in notable scientific publications.[40]

Darwin thought of natural selection by analogy to how farmers select crops or livestock for breeding, which he called "artificial selection"; in his early manuscripts he referred to a 'Nature' which would do the selection. At the time, other mechanisms of evolution such as evolution by genetic drift were not yet explicitly formulated, and Darwin believed that selection was likely only part of the story: "I am convinced that [it] has been the main, but not exclusive means of modification."[41] In a letter to Charles Lyell in September 1860, Darwin regretted the use of the term "Natural Selection", preferring the term "Natural Preservation".[42] For Darwin and his contemporaries, natural selection was essentially synonymous with evolution by natural selection. After the publication of *The Origin of Species*, educated people generally accepted that evolution had occurred in some form. However, natural selection remained controversial as a mechanism, partly because it was perceived to be too weak to explain the range of observed characteristics of living organisms, and partly because even supporters of evolution balked at its "unguided" and non-progressive nature,[43] a response that has been characterized as the single most significant impediment to the idea's acceptance.[44] However, some thinkers enthusiastically embraced natural selection; after reading Darwin, Herbert Spencer introduced the term *survival of the fittest*, which became a popular summary of the theory.[45] The fifth edition of *On the Origin of Species* published in 1869 included Spencer's phrase as an alternative to natural selection, with credit given: "But the expression often used by Mr. Herbert Spencer, of the Survival of the Fittest, is more accurate, and is sometimes equally convenient."[46] Although the phrase is still often used by non-biologists, modern biologists avoid it because it is tautological if "fittest" is read to mean "functionally superior" and is applied to individuals rather than considered as an averaged quantity over populations.[47]

Modern evolutionary synthesis

Natural selection relies crucially on the idea of heredity, but it was developed long before the basic concepts of genetics. Although the Austrian monk Gregor Mendel, the father of modern genetics, was a contemporary of Darwin's, his work would lie in obscurity until the early 20th century. Only after the integration of Darwin's theory of evolution with a complex statistical appreciation of Gregor Mendel's 're-discovered' laws of inheritance did natural selection become generally accepted by scientists. The work of Ronald Fisher (who developed the required mathematical language and the genetical theory of natural selection),[2] J.B.S. Haldane (who introduced the concept of the "cost" of natural selection),[48] Sewall Wright (who elucidated the nature of selection and adaptation),[49] Theodosius Dobzhansky (who established the idea that mutation, by creating genetic diversity, supplied the raw material for natural selection: see Genetics and the Origin of Species),[50] William Hamilton (who conceived of kin selection), Ernst Mayr (who recognised the key importance of reproductive isolation for speciation: see Systematics and the Origin of Species)[51] and many others formed the modern evolutionary synthesis. This synthesis cemented natural selection as the foundation of evolutionary theory, where it remains today.

Impact of the idea

Darwin's ideas, along with those of Adam Smith and Karl Marx, had a profound influence on 19th century thought. Perhaps the most radical claim of the theory of evolution through natural selection is that "elaborately constructed forms, so different from each other, and dependent on each other in so complex a manner" evolved from the simplest forms of life by a few simple principles. This claim inspired some of Darwin's most ardent supporters—and provoked the most profound opposition. The radicalism of natural selection, according to Stephen Jay Gould,[52] lay in its power to "dethrone some of the deepest and most traditional comforts of Western thought". In particular, it challenged long-standing beliefs in such concepts as a special and exalted place for humans in the natural world and a benevolent creator whose intentions were reflected in nature's order and design.

Cell and molecular biology

In the 19th century, Wilhelm Roux, a founder of modern embryology, wrote a book entitled « Der Kampf der Teile im Organismus » (The struggle of parts in the organism) in which he suggested that the development of an organism results from a Darwinian competition between the parts of the embryo, occurring at all levels, from molecules to organs. In recent years, a modern version of this theory has been proposed by Jean-Jacques Kupiec [53]. According to this cellular Darwinism [54], stochasticity at the molecular level generates diversity in cell types whereas cell interactions impose a characteristic order on the developing embryo.

Social and psychological theory

The social implications of the theory of evolution by natural selection also became the source of continuing controversy. Friedrich Engels, a German political philosopher and co-originator of the ideology of communism, wrote in 1872 that "Darwin did not know what a bitter satire he wrote on mankind when he showed that free competition, the struggle for existence, which the economists celebrate as the highest historical achievement, is the normal state of the animal kingdom".[55] Interpretation of natural selection as necessarily 'progressive', leading to increasing 'advances' in intelligence and civilisation, was used as a justification for colonialism and policies of eugenics, as well as broader sociopolitical positions now described as Social Darwinism. Konrad Lorenz won the Nobel Prize in Physiology or Medicine in 1973 for his analysis of animal behavior in terms of the role of natural selection (particularly group selection). However, in Germany in 1940, in writings that he subsequently disowned, he used the theory as a justification for policies of the Nazi state. He wrote "... selection for toughness, heroism, and social utility...must be accomplished by some human institution, if mankind, in default of selective factors, is not to be ruined by domestication-induced degeneracy. The racial idea as the basis of our state has already accomplished much in this respect."[56] Others have developed ideas that human societies and culture evolve by mechanisms that are analogous to those that apply to evolution of species.[57]

More recently, work among anthropologists and psychologists has led to the development of sociobiology and later evolutionary psychology, a field that attempts to explain features of human psychology in terms of adaptation to the ancestral environment. The most prominent such example, notably advanced in the early work of Noam Chomsky and later by Steven Pinker, is the hypothesis that the human brain is adapted to acquire the grammatical rules of natural language.[58] Other aspects of human behavior and social structures, from specific cultural norms such as incest avoidance to broader patterns such as gender roles, have been hypothesized to have similar origins as adaptations to the early environment in which modern humans evolved. By analogy to the action of natural selection on genes, the concept of memes – "units of cultural transmission", or culture's equivalents of genes undergoing selection and recombination – has arisen, first described in this form by Richard Dawkins[59] and subsequently expanded upon by philosophers such as Daniel Dennett as explanations for complex cultural activities, including human consciousness.[60] Extensions of the theory of natural selection to such a wide range of cultural phenomena have been distinctly controversial and are not widely accepted.[61]

Information and systems theory

In 1922, Alfred Lotka proposed that natural selection might be understood as a physical principle which could be described in terms of the use of energy by a system,[62] a concept that was later developed by Howard Odum as the maximum power principle whereby evolutionary systems with selective advantage maximise the rate of useful energy transformation. Such concepts are sometimes relevant in the study of applied thermodynamics.

The principles of natural selection have inspired a variety of computational techniques, such as "soft" artificial life, that simulate selective processes and can be highly efficient in 'adapting' entities to an environment defined by a specified fitness function.[63] For example, a class of heuristic optimization algorithms known as genetic algorithms, pioneered by John Holland in the 1970s and expanded upon by David E. Goldberg,[64] identify optimal solutions by simulated reproduction and mutation of a population of solutions defined by an initial probability distribution.[65] Such algorithms are particularly useful when applied to problems whose solution landscape is very rough or has many local minima.

Genetic basis of natural selection

The idea of natural selection predates the understanding of genetics. We now have a much better idea of the biology underlying heritability, which is the basis of natural selection.

Genotype and Phenotype

See also: Genotype-phenotype distinction.

Natural selection acts on an organism's phenotype, or physical characteristics. Phenotype is determined by an organism's genetic make-up (genotype) and the environment in which the organism lives. Often, natural selection acts on specific traits of an individual, and the terms phenotype and genotype are used narrowly to indicate these specific traits.

When different organisms in a population possess different versions of a gene for a certain trait, each of these versions is known as an allele. It is this genetic variation that underlies phenotypic traits. A typical example is that certain combinations of genes for eye color in humans which, for instance, give rise to the phenotype of blue eyes. (On the other hand, when all the organisms in a population share the same allele for a particular trait, and this state is stable over time, the allele is said to be *fixed* in that population.)

Some traits are governed by only a single gene, but most traits are influenced by the interactions of many genes. A variation in one of the many genes that contributes to a trait may have only a small effect on the phenotype; together, these genes can produce a continuum of possible phenotypic values.[66]

Directionality of selection

When some component of a trait is heritable, selection will alter the frequencies of the different alleles, or variants of the gene that produces the variants of the trait. Selection can be divided into three classes, on the basis of its effect on allele frequencies.[67]

Directional selection occurs when a certain allele has a greater fitness than others, resulting in an increase of its frequency. This process can continue until the allele is fixed and the entire population shares the fitter phenotype. It is directional selection that is illustrated in the antibiotic resistance example above.

Far more common is stabilizing selection (which is commonly **confused** with *purifying selection*[68] [69]), which lowers the frequency of alleles that have a deleterious effect on the phenotype – that is, produce organisms of lower fitness. This process can continue until the allele is eliminated from the population. Purifying selection results in functional genetic features, such as protein-coding genes or regulatory sequences, being conserved over time due to selective pressure against deleterious variants.

Finally, a number of forms of balancing selection exist, which do not result in fixation, but maintain an allele at intermediate frequencies in a population. This can occur in diploid species (that is, those that have two pairs of chromosomes) when heterozygote individuals, who have different alleles on each chromosome at a single genetic locus, have a higher fitness than homozygote individuals that have two of the same alleles. This is called heterozygote advantage or overdominance, of which the best-known example is the malarial resistance observed in heterozygous humans who carry only one copy of the gene for sickle cell anemia. Maintenance of allelic variation can also occur through disruptive or diversifying selection, which favors genotypes that depart from the average in either direction (that is, the opposite of overdominance), and can result in a bimodal distribution of trait values. Finally, balancing selection can occur through frequency-dependent selection, where the fitness of one particular phenotype depends on the distribution of other phenotypes in the population. The principles of game theory have been applied to understand the fitness distributions in these situations, particularly in the study of kin selection and the evolution of reciprocal altruism.[70] [71]

Selection and genetic variation

A portion of all genetic variation is functionally neutral in that it produces no phenotypic effect or significant difference in fitness; the hypothesis that this variation accounts for a large fraction of observed genetic diversity is known as the neutral theory of molecular evolution and was originated by Motoo Kimura. When genetic variation does not result in differences in fitness, selection cannot *directly* affect the frequency of such variation. As a result, the genetic variation at those sites will be higher than at sites where variation does influence fitness.[67] However, after a period with no new mutation, the genetic variation at these sites will be eliminated due to genetic drift.

Mutation selection balance

Natural selection results in the reduction of genetic variation through the elimination of maladapted individuals and consequently of the mutations that caused the maladaptation. At the same time, new mutations occur, resulting in a mutation-selection balance. The exact outcome of the two processes depends both on the rate at which new mutations occur and on the strength of the natural selection, which is a function of how unfavorable the mutation proves to be. Consequently, changes in the mutation rate or the selection pressure will result in a different mutation-selection balance.

Genetic linkage

Genetic linkage occurs when the loci of two alleles are *linked*, or in close proximity to each other on the chromosome. During the formation of gametes, recombination of the genetic material results in reshuffling of the alleles. However, the chance that such a reshuffle occurs between two alleles depends on the distance between those alleles; the closer the alleles are to each other, the less likely it is that such a reshuffle will occur. Consequently, when selection targets one allele, this automatically results in selection of the other allele as well; through this mechanism, selection can have a strong influence on patterns of variation in the genome.

Selective sweeps occur when an allele becomes more common in a population as a result of positive selection. As the prevalence of one allele increases, linked alleles can also become more common, whether they are neutral or even slightly deleterious. This is called *genetic hitchhiking*. A strong selective sweep results in a region of the genome where the positively selected haplotype (the allele and its neighbours) are essentially the only ones that exist in the population.

Whether a selective sweep has occurred or not can be investigated by measuring linkage disequilibrium, or whether a given haplotype is overrepresented in the population. Normally, genetic recombination results in a reshuffling of the different alleles within a haplotype, and none of the haplotypes will dominate the population. However, during a selective sweep, selection for a specific allele will also result in selection of neighbouring alleles. Therefore, the presence of strong linkage disequilibrium might indicate that there has been a 'recent' selective sweep, and this can be used to identify sites recently under selection.

Background selection is the opposite of a selective sweep. If a specific site experiences strong and persistent purifying selection, linked variation will tend to be weeded out along with it, producing a region in the genome of low overall variability. Because background selection is a result of deleterious new mutations, which can occur randomly in any haplotype, it produces no linkage disequilibrium.

See also

- Artificial selection
- Co-evolution
- Gene-centered view of evolution
- Negative selection
- Unit of selection

Further reading

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External links

- *The Origin of Species* by Charles Darwin [74] – Chapter 4,Natural Selection
- Natural Selection [75]- Modeling for Understanding in Science Education, University of Wisconsin
- Natural Selection [76] from University of Berkeley education website
- T. Ryan Gregory: Understanding Natural Selection: Essential Concepts and Common Misconceptions [77] Evolution: Education and Outreach

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The Genetical Theory of Natural Selection

The Genetical Theory of Natural Selection is a book by R.A. Fisher first published in 1930 by Clarendon. It is one of the most important books of the modern evolutionary synthesis[1] and is commonly cited in biology books.

Editions

A second, slightly revised edition was republished in 1958. In 1999, a third variorum edition (ISBN 0-19-850440-3), with the original 1930 text, annotated with the 1958 alterations, notes and alterations accidentally omitted from the second edition was published, edited by Henry Bennett.

Chapters

It contains the following chapters:

1. The Nature of Inheritance [2]
2. The Fundamental Theorem of Natural Selection
3. The Evolution of Dominance
4. Variation as determined by Mutation and Selection
5. Variation etc
6. Sexual Reproduction and Sexual Selection [3]
7. Mimicry
8. Man and Society
9. The Inheritance of Human Fertility
10. Reproduction in Relation to Social Class

11. Social Selection of Fertility
12. Conditions of Permanent Civilization

Contents

In the preface, Fisher considers some general points, including that there must be an understanding of natural selection distinct from that of evolution, and that the then-recent advances in the field of genetics (see history of genetics) now allowed this. In the first chapter, Fisher considers the nature of inheritance, rejecting blending inheritance in favour of particulate inheritance. The second chapter introduces Fisher's fundamental theorem of natural selection. The third considers the evolution of dominance, which Fisher believed was strongly influenced by modifiers. The last five chapters (8-12) include Fisher's more idiosyncratic views on eugenics.

Dedication

The book is dedicated to Major Leonard Darwin, Fisher's friend, correspondent and son of Charles Darwin, "In gratitude for the encouragement, given to the author, during the last fifteen years, by discussing many of the problems dealt with in this book".

Reviews

Henry Bennett gave an account of the writing and reception of Fisher's *Genetical Theory*.[4]

Sewall Wright, who had many disagreements with Fisher, reviewed the book and wrote that it was "certain to take rank as one of the major contributions to the theory of evolution".[5] J.B.S. Haldane described it as "brilliant".[6] Reginald Punnett was negative, however.[7] '

The Genetical Theory was largely overlooked for 40 years, and in particular the fundamental theorem was misunderstood. The work had a great effect on W.D. Hamilton, who discovered it as an undergraduate at Oxford[8] and noted on the rear cover of the 1999 variorum edition:

> *This is a book which, as a student, I weighed as of equal importance to the entire rest of my undergraduate Cambridge BA course and, through the time I spent on it, I think it notched down my degree. Most chapters took me weeks, some months.*
>
> *...And little modified even by molecular genetics, Fisher's logic and ideas still underpin most of the ever broadening paths by which Darwinism continues its invasion of human thought.*
>
> *Unlike in 1958, natural selection has become part of the syllabus of our intellectual life and the topic is certainly included in every decent course in biology.*
>
> *For a book that I rate only second in importance in evolution theory to Darwin's* Origin *(this as joined with its supplement* Of Man*), and also rate as undoubtedly one of the greatest books of the twentieth century the appearance of a variorum edition is a major event...*
>
> *By the time of my ultimate graduation, will I have understood all that is true in this book and will I get a First? I doubt it. In some ways some of us have overtaken Fisher; in many, however, this brilliant, daring man is still far in front.*

The publication of the variorum edition in 1999 led to renewed interest in the work and reviews by Laurence Cook ("This is perhaps the most important book on evolutionary genetics ever written"),[9] Brian Charlesworth,[10] Jim Crow[11] and A.W.F. Edwards[12]

External links

- Full text of 1930 edition [13], Open Library

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Phylogenetics

In biology, **phylogenetics** is the study of evolutionary relatedness among various groups of organisms (for example, species or populations), which is discovered through molecular sequencing data and morphological data matrices. The term *phylogenetics* is of Greek origin from the terms *phyle/phylon* (φυλή/φῦλον), meaning "tribe, race," and *genetikos* (γενετικός), meaning "relative to birth" from *genesis* (γένεσις, "birth"). Taxonomy, the classification, identification, and naming of organisms, has been richly informed by phylogenetics but remains methodologically and logically distinct.[1] The fields overlap however in the science of phylogenetic systematics – often called "cladism" or "cladistics" –, where only phylogenetic trees are used to delimit taxa, which represent groups of lineage-connected individuals.[2] In biological systematics as a whole, phylogenetic analyses have become essential in researching the evolutionary tree of life.

Construction of a phylogenetic tree

Evolution is regarded as a branching process, whereby populations are altered over time and may speciate into separate branches, hybridize together, or terminate by extinction. This may be visualized in a phylogenetic tree.

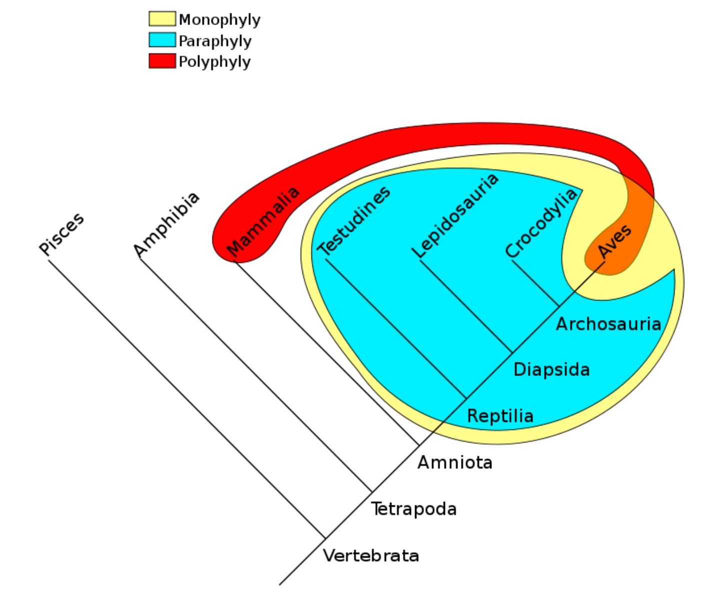
The problem posed by phylogenetics is that genetic data are only available for the present, and fossil records (osteometric data) are sporadic and less reliable. Our knowledge of how evolution operates is used to reconstruct the full tree.[3] Thus, a phylogenetic tree is based on a hypothesis of the order in which evolutionary events are assumed to have occurred.

Cladistics is the current method of choice to infer phylogenetic trees. The most commonly-used methods to infer phylogenies include parsimony, maximum likelihood, and MCMC-based Bayesian inference. Phenetics, popular in

the mid-20th century but now largely obsolete, uses distance matrix-based methods to construct trees based on overall similarity, which is often assumed to approximate phylogenetic relationships. All methods depend upon an implicit or explicit mathematical model describing the evolution of characters observed in the species included, and are usually used for molecular phylogeny, wherein the characters are aligned nucleotide or amino acid sequences.

Grouping of organisms

There are some terms that describe the nature of a grouping in such trees. For instance, all birds and reptiles are believed to have descended from a single common ancestor, so this taxonomic grouping (yellow in the diagram below) is called monophyletic. "Modern reptile" (cyan in the diagram) is a grouping that contains a common ancestor, but does not contain all descendants of that ancestor (birds are excluded). This is an example of a paraphyletic group. A grouping such as warm-blooded animals would include only mammals and birds (red/orange in the diagram) and is called polyphyletic because the members of this grouping do not include the most recent common ancestor.



Phylogenetic groups, or *taxa*, can be monophyletic, paraphyletic, or polyphyletic.

Molecular phylogenetics

The evolutionary connections between organisms are represented graphically through phylogenetic trees. Due to the fact that evolution takes place over long periods of time that cannot be observed directly, biologists must reconstruct phylogenies by inferring the evolutionary relationships among present-day organisms. Fossils can aid with the reconstruction of phylogenies; however, fossil records are often too poor to be of good help. Therefore, biologists tend to be restricted with analysing present-day organisms to identify their evolutionary relationships. Phylogenetic relationships in the past were reconstructed by looking at phenotypes, often anatomical characteristics. Today, molecular data, which includes protein and DNA sequences, are used to construct phylogenetic trees.[4]

Ernst Haeckel's recapitulation theory

During the late 19th century, Ernst Haeckel's recapitulation theory, or biogenetic law, was widely accepted. This theory was often expressed as "ontogeny recapitulates phylogeny", i.e. the development of an organism exactly mirrors the evolutionary development of the species. Haeckel's early version of this hypothesis [that the embryo mirrors *adult* evolutionary ancestors] has since been rejected, and the hypothesis amended as the embryo's development mirroring *embryos* of its evolutionary ancestors. He was accused by five professors of falsifying his images of embryos (See Ernst Haeckel). Most modern biologists recognize numerous connections between ontogeny and phylogeny, explain them using evolutionary theory, or view them as supporting evidence for that theory. Donald I. Williamson suggested that larvae and embryos represented adults in other taxa that have been transferred by hybridization (the larval transfer theory).[5] [6] However, Williamson's views do not represent mainstream thought in molecular biology[7] , and there is a significant body of evidence against the larval transfer theory.[8]

Gene transfer

In general, organisms can inherit genes in two ways: vertical gene transfer and horizontal gene transfer. Vertical gene transfer is the passage of genes from parent to offspring, and horizontal gene transfer or lateral gene transfer occurs when genes jump between unrelated organisms, a common phenomenon in prokaryotes.

Horizontal gene transfer has complicated the determination of phylogenies of organisms, and inconsistencies in phylogeny have been reported among specific groups of organisms depending on the genes used to construct evolutionary trees.

Carl Woese came up with the three-domain theory of life (eubacteria, archaea and eukaryotes) based on his discovery that the genes encoding ribosomal RNA are ancient and distributed over all lineages of life with little or no horizontal gene transfer. Therefore, rRNAs are commonly recommended as molecular clocks for reconstructing phylogenies.

This has been particularly useful for the phylogeny of microorganisms, to which the species concept does not apply and which are too morphologically simple to be classified based on phenotypic traits.

Taxon sampling and phylogenetic signal

Owing to the development of advanced sequencing techniques in molecular biology, it has become feasible to gather large amounts of data (DNA or amino acid sequences) to infer phylogenetic hypotheses. For example, it is not rare to find studies with character matrices based on whole mitochondrial genomes (~16,00 nucleotides, in many animals). However, it has been proposed that it is more important to increase the number of taxa in the matrix than to increase the number of characters, because the more taxa the more robust is the resulting phylogenetic tree. This may be partly due to the breaking up of long branches. It has been argued that this is an important reason to incorporate data from fossils into phylogenies where possible. Of course, phylogenetic data that include fossil taxa are generally based on morphology, rather than DNA data. Using simulations, Derrick Zwickl and David Hillis[9] found that increasing taxon sampling in phylogenetic inference has a positive effect on the accuracy of phylogenetic analyses.

Another important factor that affects the accuracy of tree reconstruction is whether the data analyzed actually contain a useful phylogenetic signal, a term that is used generally to denote whether related organisms tend to resemble each other with respect to their genetic material or phenotypic traits.[10] Ultimately, however, there is no way to measure whether a particular phylogenetic hypothesis is accurate or not, unless the "true" relationships among the taxa being examined are already known. The best result an empirical systematist can hope to attain is a tree with branches well-supported by the available evidence.

See also

- Bauplan
- Bioinformatics
- Biomathematics
- Cladistics
- Coalescent theory
- Computational phylogenetics
- EDGE of Existence Programme
- Important publications in phylogenetics
- Language family
- Maximum parsimony
- Molecular phylogeny
- PhyloCode
- Joe Felsenstein

- Systematics
- Phylogenetic tree
- Phylogenetic network
- Phylogenetic nomenclature
- Phylogenetics software
- Phylogenetic tree viewers
- Phylogeography
- Phylodynamics
- Phylogenetic comparative methods
- Microbial phylogenetics

Further reading

- Schuh, R. T. and A. V. Z. Brower. 2009. *Biological Systematics: principles and applications (2nd edn.)* ISBN 978-0-8014-4799-0

External links

- The Tree of Life [11]
- Interactive Tree of Life [12]
- PhyloCode [13]
- ExploreTree [14]
- UCMP Exhibit Halls: Phylogeny Wing [15]
- Willi Hennig Society [16]
- Filogenetica.org in Spanish [17]
- PhyloPat, Phylogenetic Patterns [18]
- SplitsTree [19], program for computing phylogenetic trees and unrooted phylogenetic networks
- Dendroscope [20], program for drawing phylogenetic trees and rooted phylogenetic networks
- Phylogenetic inferring on the T-REX server [21]
- Mesquite [22]
- Geneious Pro [23] all-in-one phylogenetics software
- NCBI - Systematics and Molecular Phylogenetics [24]
- What Genomes Can Tell Us About the Past [25] - lecture on phylogenetics by Sydney Brenner
- Mikko's Phylogeny Archive [26]
- Phylogenetic Reconstruction from Gene-Order Data [27]

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[7] John Timmer, "Examining science on the fringes: vital, but generally wrong" (http://arstechnica.com/science/news/2009/11/examining-science-on-the-fringes-vital-but-generally-wrong.ars), *ARS Technica*, 9 November 2009

[8] Michael W. Hart, and Richard K. Grosberg, "Caterpillars did not evolve from onychophorans by hybridogenesis" (http://www.pnas.org/content/early/2009/10/22/0910229106), *Proceedings of the National Academy of the Sciences*, 30 October 2009 (doi: 10.1073/pnas.0910229106)
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[10] Blomberg SP, Garland T Jr, Ives AR (2003). "Testing for phylogenetic signal in comparative data: behavioral traits are more labile". *Evolution* **57** (4): 717–745. PMID 12778543. PDF (http://www.biology.ucr.edu/people/faculty/Garland/BlomEA03.pdf)
[11] http://tolweb.org/tree/learn/concepts/whatisphylogeny.html
[12] http://itol.embl.de
[13] http://www.ohiou.edu/phylocode/
[14] http://exploretree.org/
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[22] http://mesquiteproject.org/mesquite/mesquite.html
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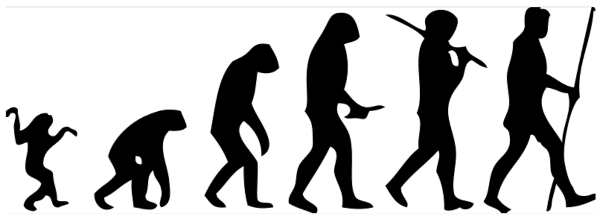
[25] http://ascb.org/ibioseminars/brenner/brenner1.cfm
[26] http://www.helsinki.fi/~mhaaramo/
[27] http://www.cs.unm.edu/~moret/poincare.pdf

Human evolution

Human evolution, or ***anthropogenesis***, is the origin and evolution of *Homo sapiens* as a distinct species from other hominids, great apes and placental mammals. The study of human evolution encompasses many scientific disciplines, including physical anthropology, primatology, archaeology, linguistics and genetics.[1]


Simplified scheme of human evolution

The term "human" in the context of human evolution refers to the genus *Homo*, but studies of human evolution usually include other hominids, such as the Australopithecines, from which the genus *Homo* had diverged by about 2.3 to 2.4 million years ago in Africa.[2] [3] Scientists have estimated that humans branched off from their common ancestor with chimpanzees - the only other living hominins - about 5–7 million years ago. Several species of *Homo* evolved and are now extinct. These include *Homo erectus*, which inhabited Asia, and *Homo neanderthalensis*, which inhabited Europe. Archaic *Homo sapiens* evolved between 400,000 and 250,000 years ago.

The dominant view among scientists concerning the origin of anatomically modern humans is the "Out of Africa" or recent African origin hypothesis,[4] [5] [6] [7] which argues that *H. sapiens* arose in Africa and migrated out of the continent around 50-100,000 years ago, replacing populations of *H. erectus* in Asia and *H. neanderthalensis* in Europe. Scientists supporting the alternative multiregional hypothesis argue that *H. sapiens* evolved as geographically separate but interbreeding populations stemming from a worldwide migration of *H. erectus* out of Africa nearly 2.5 million years ago.

History of ideas about human evolution

The word *homo*, the name of the biological genus to which humans belong, is Latin for "human". It was chosen originally by Carolus Linnaeus in his classification system. The word "human" is from the Latin *humanus*, the adjectival form of *homo*. The Latin "homo" derives from the Indo-European root, *dhghem*, or "earth".[8]

Carolus Linnaeus and other scientists of his time also considered the great apes to be the closest relatives of human beings due to morphological and anatomical similarities. The possibility of linking humans with earlier apes by descent only became clear after 1859 with the publication of Charles Darwin's *On the Origin of Species*. This argued for the idea of the evolution of new species from earlier ones. Darwin's book did not address the question of human evolution, saying only that "Light will be thrown on the origin of man and his history".

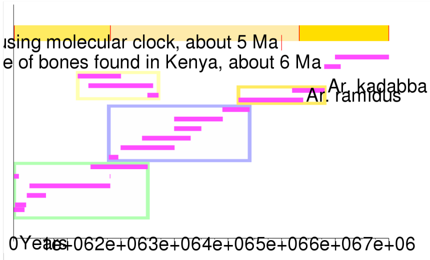
The first debates about the nature of human evolution arose between Thomas Huxley and Richard Owen. Huxley argued for human evolution from apes by illustrating many of the similarities and differences between humans and apes and did so particularly in his 1863 book *Evidence as to Man's Place in Nature*. However, many of Darwin's early supporters (such as Alfred Russel Wallace and Charles Lyell) did not agree that the origin of the mental capacities and the moral sensibilities of humans could be explained by natural selection. Darwin applied the theory of evolution and sexual selection to humans when he published *The Descent of Man* in 1871.[9]

Fossil Hominid Evolution Display at The Museum of Osteology, Oklahoma City, USA.

A major problem was the lack of fossil intermediaries. It was only in the 1920s that such fossils were discovered in Africa. In 1925, Raymond Dart described *Australopithecus africanus*. The type specimen was the Taung Child, an Australopithecine infant discovered in a cave. The child's remains were a remarkably well-preserved tiny skull and an endocranial cast of the individual's brain. Although the brain was small (410 cm^3), its shape was rounded, unlike that of chimpanzees and gorillas, and more like a modern human brain. Also, the specimen showed short canine teeth, and the position of the foramen magnum was evidence of bipedal locomotion. All of these traits convinced Dart that the Taung baby was a bipedal human ancestor, a transitional form between apes and humans.

The classification of humans and their relatives has changed considerably over time. The gracile Australopithecines are now thought to be ancestors of the genus *Homo*, the group to which modern humans belong. Both Australopithecines and *Homo sapiens* are part of the tribe Hominini. Recent data suggests Australopithecines were a diverse group and that *A. africanus* may not be a direct ancestor of modern humans. Reclassification of Australopithecines that originally were split into either gracile or robust varieties has put the latter into a family of its own, *Paranthropus*. Taxonomists place humans, Australopithecines and related species in the same family as other great apes, in the Hominidae.

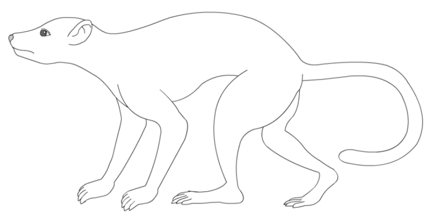
Hominin species distributed through time



Note: 1e+06 years = 1 × 10^6 years = 1 million years ago = 1 Ma

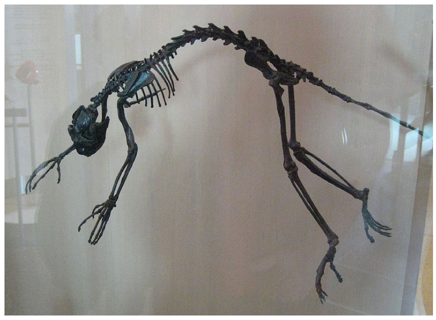
Before *Homo*

Evolution of apes



Plesiadapis.

The evolutionary history of the primates can be traced back 65 million years, as one of the oldest of all surviving placental mammal groups. The oldest known primate-like mammal species, the Plesiadapis, come from North America, but they were widespread in Eurasia and Africa during the tropical conditions of the Paleocene and Eocene.



Notharctus.

With the beginning of modern climates, marked by the formation of the first Antarctic ice in the early Oligocene around 30 million years ago. A primate from this time was *Notharctus*. Fossil evidence found in Germany in the 1980s was determined to be about 16.5 million years old, some 1.5 million years older than similar species from East Africa and challenging the original theory regarding human ancestry originating on the African continent.

David Begun[10] says that these primates flourished in Eurasia and that the lineage leading to the African apes and humans— including Dryopithecus—migrated south from Europe or Western Asia into Africa. The surviving tropical population, which is seen most completely in the upper Eocene and lowermost Oligocene fossil beds of the Fayum depression southwest of Cairo, gave rise to all living primates—lemurs of Madagascar, lorises of Southeast Asia, galagos or "bush babies" of Africa, and the anthropoids; platyrrhines or New World monkeys, and catarrhines or Old World monkeys and the great apes and humans.

The earliest known catarrhine is *Kamoyapithecus* from uppermost Oligocene at Eragaleit in the northern Kenya Rift Valley, dated to 24 million years ago. Its ancestry is generally thought to be species related to *Aegyptopithecus*, *Propliopithecus*, and *Parapithecus* from the Fayum, at around 35 million years ago. There are no fossils from the intervening 11 million years.

In the early Miocene, after 22 million years ago, the many kinds of arboreally-adapted primitive catarrhines from East Africa suggest a long history of prior diversification. Fossils at 20 million years ago include fragments attributed to *Victoriapithecus*, the earliest Old World Monkey. Among the genera thought to be in the ape lineage leading up to 13 million years ago are *Proconsul*, *Rangwapithecus*, *Dendropithecus*, *Limnopithecus*, *Nacholapithecus*, *Equatorius*, *Nyanzapithecus*, *Afropithecus*, *Heliopithecus*, and *Kenyapithecus*, all from East Africa. The presence of other generalized non-cercopithecids of middle Miocene age from sites far distant—*Otavipithecus* from cave deposits in Namibia, and *Pierolapithecus* and *Dryopithecus* from France, Spain and Austria—is evidence of a wide diversity of forms across Africa and the Mediterranean basin during the relatively warm and equable climatic regimes of the early and middle Miocene. The youngest of the Miocene hominoids, *Oreopithecus*, is from 9 million year old coal beds in Italy.

Reconstructed tailless *Proconsul* skeleton.

Molecular evidence indicates that the lineage of gibbons (family Hylobatidae) became distinct from Great Apes between 18 and 12 million years ago, and that of orangutans (subfamily Ponginae) became distinct from the other Great Apes at about 12 million years; there are no fossils that clearly document the ancestry of gibbons, which may have originated in a so-far-unknown South East Asian hominoid population, but fossil proto-orangutans may be represented by *Ramapithecus* from India and *Griphopithecus* from Turkey, dated to around 10 million years ago.

Divergence of the human lineage from other Great Apes

Species close to the last common ancestor of gorillas, chimpanzees and humans may be represented by *Nakalipithecus* fossils found in Kenya and *Ouranopithecus* found in Greece. Molecular evidence suggests that between 8 and 4 million years ago, first the gorillas, and then the chimpanzees (genus *Pan*) split off from the line leading to the humans; human DNA is approximately 98.4% identical to that of chimpanzees when comparing single nucleotide polymorphisms (see Human evolutionary genetics). The fossil record of gorillas and chimpanzees is quite limited. Both poor preservation (rain forest soils tend to be acidic and dissolve bone) and sampling bias probably contribute to this problem.

Other hominines likely adapted to the drier environments outside the equatorial belt, along with antelopes, hyenas, dogs, pigs, elephants, and horses. The equatorial belt contracted after about 8 million years ago. Fossils of these hominans - the species in the human lineage following divergence from the chimpanzees - are relatively well known. The earliest are *Sahelanthropus tchadensis* (7 Ma) and *Orrorin tugenensis* (6 Ma), followed by:

- *Ardipithecus* (5.5–4.4 Ma), with species *Ar. kadabba* and *Ar. ramidus*;
- *Australopithecus* (4–2 Ma), with species *Au. anamensis*, *Au. afarensis*, *Au. africanus*, *Au. bahrelghazali*, and *Au. garhi*;
- *Kenyanthropus* (3–2.7 Ma), with species *Kenyanthropus platyops*
- *Paranthropus* (3–1.2 Ma), with species *P. aethiopicus*, *P. boisei*, and *P. robustus*;
- *Homo* (2 Ma–present), with species *Homo habilis*, *Homo rudolfensis*, *Homo ergaster*, *Homo georgicus*, *Homo antecessor*, *Homo cepranensis*, *Homo erectus*, *Homo heidelbergensis*, *Homo rhodesiensis*, *Homo neanderthalensis*, *Homo sapiens idaltu*, *Archaic Homo sapiens*, *Homo floresiensis*

Genus *Homo*

Homo sapiens is the only extant species of its genus, *Homo*. While some other, extinct, *Homo* species might have been ancestors of *H. sapiens*, many were likely our "cousins", having speciated away from our ancestral line.[11] There is not yet a consensus as to which of these groups should count as separate species and which as subspecies. In some cases this is due to the dearth of fossils, in other cases it is due to the slight differences used to classify species in the *Homo* genus. The Sahara pump theory (describing an occasionally passable "wet" Sahara Desert) provides an explanation of the early variation in the genus *Homo*.

Based on archaeological and paleontological evidence, it has been possible to infer the ancient dietary practices of various *Homo* species and to study the role of diet in physical and behavioral evolution within *Homo*.[12] [13] [14] [15] [16]

Habilis

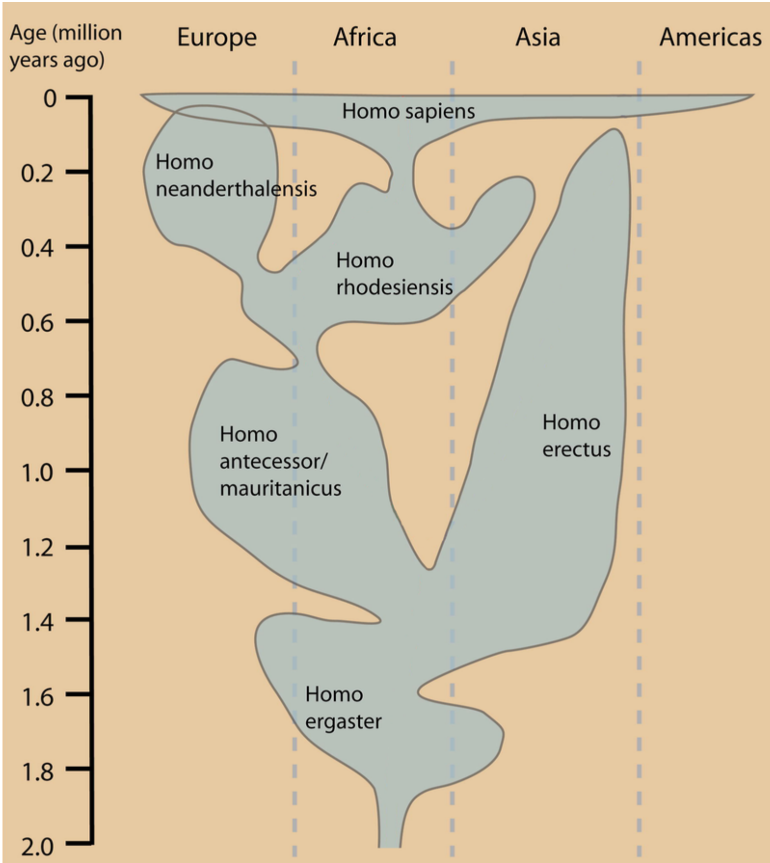
H. habilis lived from about 2.4 to 1.4 Ma. *H. habilis*, the first species of the genus *Homo*, evolved in South and East Africa in the late Pliocene or early Pleistocene, 2.5–2 Ma, when it diverged from the Australopithecines. *H. habilis* had smaller molars and larger brains than the Australopithecines, and made tools from stone and perhaps animal bones. One of the first known hominids, it was nicknamed 'handy man' by its discoverer, Louis Leakey due to its association with stone tools. Some scientists have proposed moving this species out of *Homo* and into *Australopithecus* due to the morphology of its skeleton being more adapted to living on trees rather than to moving on two legs like *H. sapiens*.[17]

Rudolfensis and *Georgicus*

These are proposed species names for fossils from about 1.9–1.6 Ma, the relation of which with *H. habilis* is not yet clear.

- *H. rudolfensis* refers to a single, incomplete skull from Kenya. Scientists have suggested that this was another *H. habilis*, but this has not been confirmed.[18]
- *H. georgicus*, from Georgia, may be an intermediate form between *H. habilis* and *H. erectus*,[19] or a sub-species of *H. erectus*.[20]

Ergaster and *Erectus*



One current view of the temporal and geographical distribution of hominid populations.[21] Other interpretations differ mainly in the taxonomy and geographical distribution of hominid species.

The first fossils of *Homo erectus* were discovered by Dutch physician Eugene Dubois in 1891 on the Indonesian island of Java. He originally gave the material the name *Pithecanthropus erectus* based on its morphology that he considered to be intermediate between that of humans and apes.[22] *H. erectus* lived from about 1.8 Ma to about 70,000 years ago (which would indicate that they were probably wiped out by the Toba catastrophe; however, *Homo erectus soloensis* and *Homo floresiensis* survived it). Often the early phase, from 1.8 to 1.25 Ma, is considered to be a separate species, *H. ergaster*, or it is seen as a subspecies of *H. erectus*, *Homo erectus ergaster*.

In the early Pleistocene, 1.5–1 Ma, in Africa, Asia, and Europe, some populations of *Homo habilis* are thought to have evolved larger brains and made more elaborate stone tools; these differences and others are sufficient for anthropologists to classify them as a new species, *H. erectus*. In addition *H. erectus* was the first human ancestor to walk truly upright.[23] This was made possible by the evolution of locking knees and a different location of the foramen magnum (the hole in the skull where the spine enters). They may have used fire to cook their meat.

A famous example of *Homo erectus* is Peking Man; others were found in Asia (notably in Indonesia), Africa, and Europe. Many paleoanthropologists now use the term *H. ergaster* for the non-Asian forms of this group, and reserve *H. erectus* only for those fossils that are found in Asia and meet certain skeletal and dental requirements which differ slightly from *H. ergaster*.

Cepranensis and *Antecessor*

These are proposed as species that may be intermediate between *H. erectus* and *H. heidelbergensis*.

- *H. antecessor* is known from fossils from Spain and England that are dated 1.2 Ma–500 ka.[24] [25]
- *H. cepranensis* refers to a single skull cap from Italy, estimated to be about 800,000 years old.[26]

Heidelbergensis

H. heidelbergensis (Heidelberg Man) lived from about 800,000 to about 300,000 years ago. Also proposed as *Homo sapiens heidelbergensis* or *Homo sapiens paleohungaricus*.[27]

Rhodesiensis, and the Gawis cranium

- *H. rhodesiensis*, estimated to be 300,000–125,000 years old. Most current experts believe Rhodesian Man to be within the group of *Homo heidelbergensis* though other designations such as Archaic Homo sapiens and Homo sapiens rhodesiensis have also been proposed.
- In February 2006 a fossil, the Gawis cranium, was found which might possibly be a species intermediate between *H. erectus* and *H. sapiens* or one of many evolutionary dead ends. The skull from Gawis, Ethiopia, is believed to be 500,000–250,000 years old. Only summary details are known, and no peer reviewed studies have been released by the finding team. Gawis man's facial features suggest its being either an intermediate species or an example of a "Bodo man" female.[28]

Neanderthalensis

Le Ferrassie Neanderthal skull (cast)

H. neanderthalensis lived from 400,000[29] years ago. Also proposed as *Homo sapiens neanderthalensis*: there is ongoing debate over whether the "Neanderthal Man" was a separate species, *Homo neanderthalensis*, or a subspecies of *H. sapiens*.[30] While the debate remains unsettled, evidence from sequencing mitochondrial DNA indicates that no significant gene flow occurred between *H. neanderthalensis* and *H. sapiens*, and, therefore, the two were separate species that shared a common ancestor about 660,000 years ago.[31] [32] In 1997, Mark Stoneking stated: "These results [based on mitochondrial DNA extracted from Neanderthal bone] indicate that Neanderthals did not contribute mitochondrial DNA to modern humans… Neanderthals are not our ancestors." Subsequent investigation of a second source of Neanderthal DNA supported these findings.[33] However, supporters of the multiregional hypothesis point to recent studies indicating non-African nuclear DNA heritage dating to one Ma,[34] although the reliability of these studies has been questioned.[35] Competition from *Homo sapiens* probably contributed to Neanderthal extinction.[36] [37] They could have coexisted in Europe for as long as 10,000 years.[38]

Sapiens

H. sapiens (the adjective *sapiens* is Latin for "wise" or "intelligent") has lived from about 250,000 years ago to the present. Between 400,000 years ago and the second interglacial period in the Middle Pleistocene, around 250,000 years ago, the trend in skull expansion and the elaboration of stone tool technologies developed, providing evidence for a transition from *H. erectus* to *H. sapiens*. The direct evidence suggests there was a migration of *H. erectus* out of Africa, then a further speciation of *H. sapiens* from *H. erectus* in Africa. A subsequent migration within and out of Africa eventually replaced the earlier dispersed *H. erectus*. This migration and origin theory is usually referred to as the *recent single origin* or Out of Africa theory. Current evidence does not preclude some multiregional evolution or some admixture of the migrant *H. sapiens* with existing *Homo* populations. This is a hotly debated area of paleoanthropology.

Current research has established that humans are genetically highly homogenous; that is, the DNA of individuals is more alike than usual for most species, which may have resulted from their relatively recent evolution or the possibility of a population bottleneck resulting from cataclysmic natural events such as the Toba catastrophe.[39] [40] [41] Distinctive genetic characteristics have arisen, however, primarily as the result of small groups of people moving into new environmental circumstances. These adapted traits are a very small component of the *Homo sapiens* genome, but include various characteristics such as skin color and nose form, in addition to internal characteristics such as the ability to breathe more efficiently in high altitudes.

H. sapiens idaltu, from Ethiopia, is a possible extinct sub-species who lived from about 160,000 years ago.

Floresiensis

H. floresiensis, which lived from approximately 100,000 to 12,000 before present, has been nicknamed *hobbit* for its small size, possibly a result of insular dwarfism.[42] *H. floresiensis* is intriguing both for its size and its age, being a concrete example of a recent species of the genus *Homo* that exhibits derived traits not shared with modern humans. In other words, *H. floresiensis* share a common ancestor with modern humans, but split from the modern human lineage and followed a distinct evolutionary path. The main find was a skeleton believed to be a woman of about 30 years of age. Found in 2003 it has been dated to approximately 18,000 years old. The living woman was estimated to be one meter in height, with a brain volume of just 380 cm^3 (considered small for a chimpanzee and less than a third of the *H. sapiens* average of 1400 cm^3).

However, there is an ongoing debate over whether *H. floresiensis* is indeed a separate species.[43] Some scientists presently believe that *H. floresiensis* was a modern *H. sapiens* suffering from pathological dwarfism.[44] This hypothesis is supported in part, because some modern humans who live on Flores, the island where the skeleton was found, are pygmies. This coupled with pathological dwarfism could indeed create a hobbit-like human. The other major attack on *H. floresiensis* is that it was found with tools only associated with *H. sapiens*.[44]

Woman X

There were at least three different forms of humans in southern Siberia around 40,000 years ago – *H. sapiens*, *H. neanderthalensis*, and unknown type of hominin, nicknamed "Woman X" for the time being.[38]

Comparative table of *Homo* species

Species	Lived when (Ma)	Lived where	Adult height	Adult mass	Cranial capacity (cm³)	Fossil record	Discovery / publication of name
H. habilis	2.3 – 1.4	Africa	1.0–1.5 m (3.3–4.9 ft)	33–55 kg (73–120 lb)	510–660	Many	1960/1964
H. rudolfensis	1.9	Kenya				1 skull	1972/1986
H. ergaster	1.9 – 1.4	Eastern and Southern Africa	1.9 m (6.2 ft)		700–850	Many	1975
H. georgicus	1.8	Georgia			600	4 individuals	1999/2002
H. erectus	1.5 – 0.2	Africa, Eurasia (Java, China, India, Caucasus)	1.8 m (5.9 ft)	60 kg (130 lb)	850 (early) – 1,100 (late)	Many	1891/1892
H. antecessor	1.2 – 0.8	Spain	1.75 m (5.7 ft)	90 kg (200 lb)	1,000	2 sites	1997
H. cepranensis	0.9 – 0.8?	Italy			1,000	1 skull cap	1994/2003
H. heidelbergensis	0.6 – 0.35	Europe, Africa, China	1.8 m (5.9 ft)	60 kg (130 lb)	1,100–1,400	Many	1908
H. neanderthalensis	0.35 – 0.03	Europe, Western Asia	1.6 m (5.2 ft)	55–70 kg (120–150 lb) (heavily built)	1,200–1,900	Many	(1829)/1864
H. rhodesiensis	0.3 – 0.12	Zambia			1,300	Very few	1921

***H. sapiens sapiens* (modern humans)**	0.2 – present	Worldwide	1.4–1.9 m (4.6–6.2 ft)	50–100 kg (110–220 lb)	1,000–1,850	Still living	—/1758
H. sapiens idaltu	0.16 – 0.15	Ethiopia			1,450	3 craniums	1997/2003
H. floresiensis	0.10? – 0.012	Indonesia	1.0 m (3.3 ft)	25 kg (55 lb)	400	7 individuals	2003/2004

Use of tools

"A sharp rock", an Oldowan pebble tool, the most basic of human stone tools

Using tools has been interpreted as a sign of intelligence, and it has been theorized that tool use may have stimulated certain aspects of human evolution—most notably the continued expansion of the human brain. Paleontology has yet to explain the expansion of this organ over millions of years despite being extremely demanding in terms of energy consumption. The brain of a modern human consumes about 20 watts (400 kilocalories per day), which is one fifth of the energy consumption of a human body. Increased tool use would allow hunting for energy-rich meat products, and would enable processing more energy-rich plant products. Researchers have suggested that early hominids were thus under evolutionary pressure to increase their capacity to create and use tools.[45]

Fire, one of the greatest human discoveries

Precisely when early humans started to use tools is difficult to determine, because the more primitive these tools are (for example, sharp-edged stones) the more difficult it is to decide whether they are natural objects or human artifacts. There is some evidence that the australopithecines (4 Ma) may have used broken bones as tools, but this is debated.

An Acheulean hand axe, the pinnacle of *Homo erectus* stone working

It should be noted that many species make and use tools, but it is the human species that dominates the areas of making and using more complex tools. A good question is, what species made and used the first tools? The oldest known tools are the "Oldowan stone tools" from Ethiopia. It was discovered that these tools are from 2.5 to 2.6 million years old, which predates the earliest known "Homo" species. There is no known evidence that any "Homo" specimens appeared by 2.5 Ma. A Homo fossil was found near some Oldowan tools, and its age was noted at 2.3 million years old, suggesting that maybe the Homo species did indeed create and use these tools. It is surely possible, but not solid evidence. Bernard Wood noted that "Paranthropus" coexisted with the early Homo species in the area of the "Oldowan Industrial Complex" over roughly the same span of time. Although there is no direct evidence that points to Paranthropus as the tool makers, their anatomy lends to indirect evidence of their capabilities in this area. Most paleoanthropologists agree that the early "Homo"

species were indeed responsible for most of the Oldowan tools found. They argue that when most of the Oldowan tools were found in association with human fossils, Homo was always present, but Paranthropus was not.[46]

In 1994, Randall Susman used the anatomy of opposable thumbs as the basis for his argument that both the Homo and Paranthropus species were toolmakers. He compared bones and muscles of human and chimpanzee thumbs, finding that humans have 3 muscles that chimps lack. Humans also have thicker metacarpals with broader heads, making the human hand more successful at precision grasping than the chimpanzee hand. Susman defended that modern anatomy of the human thumb is an evolutionary response to the requirements associated with making and handling tools and that both species were indeed toolmakers.[46]

Venus of Willendorf, an example of Paleolithic art

Stone tools

Stone tools are first attested around 2.6 Ma, when *H. habilis* in Eastern Africa used so-called pebble tools, choppers made out of round pebbles that had been split by simple strikes.[47] This marks the beginning of the Paleolithic, or Old Stone Age; its end is taken to be the end of the last Ice Age, around 10,000 years ago. The Paleolithic is subdivided into the Lower Paleolithic (Early Stone Age, ending around 350,000–300,000 years ago), the Middle Paleolithic (Middle Stone Age, until 50,000–30,000 years ago), and the Upper Paleolithic.

The period from 700,000–300,000 years ago is also known as the Acheulean, when *H. ergaster* (or *erectus*) made large stone hand-axes out of flint and quartzite, at first quite rough (Early Acheulian), later "retouched" by additional, more subtle strikes at the sides of the flakes. After 350,000 BP (Before Present) the more refined so-called Levallois technique was developed. It consisted of a series of consecutive strikes, by which scrapers, slicers ("racloirs"), needles, and flattened needles were made.[47] Finally, after about 50,000 BP, ever more refined and specialized flint tools were made by the Neanderthals and the immigrant Cro-Magnons (knives, blades, skimmers). In this period they also started to make tools out of bone.

Modern humans and the "Great Leap Forward" debate

Until about 50,000–40,000 years ago the use of stone tools seems to have progressed stepwise. Each phase (*H. habilis*, *H. ergaster*, *H. neanderthalensis*) started at a higher level than the previous one, but once that phase started further development was slow. These *Homo* species were culturally conservative, but after 50,000 BP modern human culture started to change at a much greater speed. Jared Diamond, author of *The Third Chimpanzee*, and some anthropologists characterize this as a "Great Leap Forward."

Modern humans started burying their dead, making clothing out of hides, developing sophisticated hunting techniques (such as using trapping pits or driving animals off cliffs), and engaging in cave painting.[48] As human culture advanced, different populations of humans introduced novelty to existing technologies: artifacts such as fish hooks, buttons and bone needles show signs of variation among different populations of humans, something that had not been seen in human cultures prior to 50,000 BP. Typically, *H. neanderthalensis* populations do not vary in their technologies.

Among concrete examples of Modern human behavior, anthropologists include specialization of tools, use of jewelery and images (such as cave drawings), organization of living space, rituals (for example, burials with grave

gifts), specialized hunting techniques, exploration of less hospitable geographical areas, and barter trade networks. Debate continues as to whether a "revolution" led to modern humans ("the big bang of human consciousness"), or whether the evolution was more gradual.[49]

Models of human evolution

Today, all humans belong to one, undivided by species barrier, population of *Homo sapiens sapiens*. However, according to the "Out of Africa" model this is not the first species of hominids: the first species of genus *Homo*, *Homo habilis*, evolved in East Africa at least 2 Ma, and members of this species populated different parts of Africa in a relatively short time. *Homo erectus* evolved more than 1.8 Ma, and by 1.5 Ma had spread throughout the Old World.

Anthropologists have been divided as to whether current human population evolved as one interconnected population (as postulated by the Multiregional Evolution hypothesis), or evolved only in East Africa, speciated, and then migrating out of Africa and replaced human populations in Eurasia (called the "Out of Africa" Model or the "Complete Replacement" Model).

Multiregional model

Multiregional evolution, a *model to account for the pattern of human evolution*, was proposed by Milford H. Wolpoff[50] in 1988.[51] Multiregional evolution holds that human evolution from the beginning of the Pleistocene 2.5 million years BP to the present day has been within a single, continuous human species, evolving worldwide to modern *Homo sapiens*.

According to the multiregional hypothesis, fossil and genomic data are evidence for worldwide human evolution and contradict the recent speciation postulated by the Recent African origin hypothesis. The fossil evidence was insufficient for Richard Leakey to resolve this debate.[52] Studies of haplogroups in Y-chromosomal DNA and mitochondrial DNA have largely supported a recent African origin.[53] Evidence from autosomal DNA also supports the Recent African origin. However the presence of archaic admixture in modern humans remains a possibility and has been suggested by some studies.[54]

Out of Africa

According to the Out of Africa model, developed by Chris Stringer and Peter Andrews, modern *H. sapiens* evolved in Africa 200,000 years ago. *Homo sapiens* began migrating from Africa between 70,000 – 50,000 years ago and eventually replaced existing hominid species in Europe and Asia.[55] [56] Out of Africa has gained support from research using mitochondrial DNA (mtDNA). After analysing genealogy trees constructed using 133 types of mtDNA, researchers concluded that all were descended from a woman from Africa, dubbed Mitochondrial Eve. Out of Africa is also supported by the fact that mitochondrial genetic diversity is highest among African populations.[57]

There are differing theories on whether there was a single exodus or several. A multiple dispersal model involves the Southern Dispersal theory,[58] which has gained support in recent years from genetic, linguistic and archaeological evidence. In this theory, there was a coastal dispersal of modern humans from the Horn of Africa around 70,000 years ago. This group helped to populate Southeast Asia and Oceania, explaining the discovery of early human sites in these areas much earlier than those in the Levant. A second wave of humans dispersed across the Sinai peninsula into Asia, resulting in the bulk of human population for Eurasia. This second group possessed a more sophisticated tool technology and was less dependent on coastal food sources than the original group. Much of the evidence for the first group's expansion would have been destroyed by the rising sea levels at the end of the Holocene era.[58] The multiple dispersal model is contradicted by studies indicating that the populations of Eurasia and the populations of Southeast Asia and Oceania are all descended from the same mitochondrial DNA lineages, which support a single migration out of Africa that gave rise to all non-African populations.[59]

The broad study of African genetic diversity headed by Dr. Sarah Tishkoff found the San people to express the greatest genetic diversity among the 113 distinct populations sampled, making them one of 14 "ancestral population clusters". The research also located the origin of modern human migration in south-western Africa, near the coastal border of Namibia and Angola.[60]

Contemporary human evolution

Natural selection is being observed in contemporary human populations, with recent findings demonstrating the population which is at risk of the severe debilitating disease kuru has significant over representation of an immune variant of the prion protein gene G127V versus non immune alleles. Scientists postulate one of the reasons for the rapid selection of this genetic variant is the lethality of the disease in non-immune persons.[61] [62] Other reported evolutionary trends in other populations include a lengthening of the reproductive period, reduction in cholesterol levels, blood glucose and blood pressure.[63]

Genetics

Human evolutionary genetics studies how one human genome differs from the other, the evolutionary past that gave rise to it, and its current effects. Differences between genomes have anthropological, medical and forensic implications and applications. Genetic data can provide important insight into human evolution.

Notable human evolution researchers

- Robert Broom, a Scottish physician and palaeontologist whose work on South Africa led to the discovery and description of the Paranthropus genus of hominins, and of "Mrs. Ples"
- James Burnett, Lord Monboddo, a British judge most famous today as a founder of modern comparative historical linguistics
- Raymond Dart, an Australian anatomist and palaeoanthropologist, whose work at Taung, in South Africa, led to the discovery of *Australopithecus africanus*
- Charles Darwin, a British naturalist who documented considerable evidence that species originate through evolutionary change
- Richard Dawkins, a British ethologist, evolutionary biologist who has promoted a gene-centered view of evolution
- J. B. S. Haldane, a British geneticist and evolutionary biologist
- William D. Hamilton, a British Evolutionary Biologist who expounded a rigorous genetic basis for kin selection, and on the evolution of HIV and other human diseases.
- Sir Alister Hardy, a British zoologist, who first hypothesised the aquatic ape theory of human evolution
- Henry McHenry, an American anthropologist who specializes in studies of human evolution, the origins of bipedality, and paleoanthropology
- Louis Leakey, an African archaeologist and naturalist whose work was important in establishing human evolutionary development in Africa
- Mary Leakey, a British archaeologist and anthropologist whose discoveries in Africa include the Laetoli footprints
- Richard Leakey, an African paleontologist and archaeologist, son of Louis and Mary Leakey
- Svante Pääbo, a Swedish biologist specializing in evolutionary genetics
- Jeffrey H. Schwartz, an American physical anthropologist and professor of biological anthropology
- Chris Stringer, anthropologist, leading proponent of the recent single origin hypothesis
- Alan Templeton, geneticist and statistician, proponent of the multiregional hypothesis
- Philip V. Tobias, a South African palaeoanthropologist is one of the world's leading authorities on the evolution of humankind

- Erik Trinkaus, a prominent American paleoanthropologist and expert on Neanderthal biology and human evolution
- Alfred Russel Wallace, a British naturalist, sometimes called the "father of biogeography", who independently from Charles Darwin proposed the principles of evolution of animal species
- Milford H. Wolpoff, an American paleoanthropologist who is the leading proponent of the multiregional evolution hypothesis.

Species list

This list is in chronological order across the page by genus.

- *Sahelanthropus*
  - *Sahelanthropus tchadensis*
- *Orrorin*
  - *Orrorin tugenensis*
- *Ardipithecus*
  - *Ardipithecus kadabba*
  - *Ardipithecus ramidus*
- *Australopithecus*
  - *Australopithecus anamensis*
  - *Australopithecus afarensis*
  - *Australopithecus bahrelghazali*
  - *Australopithecus africanus*
  - *Australopithecus garhi*
  - *Australopithecus sediba*
- *Paranthropus*
  - *Paranthropus aethiopicus*
  - *Paranthropus boisei*
  - *Paranthropus robustus*
- *Kenyanthropus*
  - *Kenyanthropus platyops*
- *Homo*
  - *Homo habilis*
  - *Homo rudolfensis*
  - *Homo ergaster*
  - *Homo georgicus*
  - *Homo erectus*
  - *Homo cepranensis*
  - *Homo antecessor*
  - *Homo heidelbergensis*
  - *Homo rhodesiensis*
  - *Homo neanderthalensis*
  - *Homo sapiens idaltu*
  - *Homo sapiens* (Cro-Magnon)
  - *Homo sapiens sapiens*
  - *Homo floresiensis*

See also

- List of human evolution fossils
- Timeline of human evolution
- Archaeogenetics
- Dual inheritance theory
- Dysgenics
- Evolutionary anthropology
- Evolutionary medicine
- Evolutionary neuroscience
- Evolution of human intelligence
- Evolution of morality
- Evolutionary origin of religions
- Evolutionary psychology
- History of Earth
- Hominid intelligence
- Human behavioral ecology
- Human skeletal changes due to bipedalism
- Human vestigiality
- Ida (fossil)
- Physical anthropology
- Sahara pump theory
- Sexual selection in human evolution
- Sociocultural evolution

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External links

- BBC: The Evolution of Man [69]
- Illustrations from *Evolution* (textbook) [70]
- Smithsonian – Homosapiens [71]
- Smithsonian – The Human Origins Program [72]
- Becoming Human: Paleoanthropology, Evolution and Human Origins, presented by Arizona State University's Institute of Human Origins [73]

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Systems psychology

Systems psychology is a branch of applied psychology that studies human behaviour and experience in complex systems. It is inspired by systems theory and systems thinking, and based on the theoretical work of Roger Barker, Gregory Bateson, Humberto Maturana and others. It is an approach in psychology, in which groups and individuals, are considered as systems in homeostasis. Alternative terms here are "systemic psychology", "systems behavior", and "systems-based psychology".

Types of systems psychology

In the scientific literature different kind of systems psychology have been mentioned:

Applied systems psychology

De Greene in 1970 described applied systems psychology as being connected with engineering psychology and human factor.

Cognitive systems theory

Cognitive systems psychology is a part of cognitive psychology and like existential psychology, attempts to dissolve the barrier between conscious and the unconscious mind.[1]

Contract-systems psychology

Contract-systems psychology is about the human systems actualization through participative organizations.[2]

Family systems psychology

Family systems psychology is a more general name for the subfield of family therapists. E.g. Murray Bowen, Michael E. Kerr, and Baard[3] and researchers have begun to theoretize a psychology of the family as a system.[4]

Organismic-systems psychology

Through the application of organismic-systems biology to human behavior Ludwig von Bertalanffy conceived and developed the organismic-systems psychology, as the theoretical prospect needed for the gradual comprehension of the various ways human personalities may evolve and how they could evolve properly, being supported by a holistic interpretation of human behavior.[5]

Related fields

Ergonomics

Ergonomics, also called "Engineering psychology" or "human factors", is the application of scientific information concerning objects, systems and environment for human use (definition adopted by the International Ergonomics Association in 2007). Ergonomics is commonly thought of as how companies design tasks and work areas to maximize the efficiency and quality of their employees' work. However, ergonomics comes into everything which involves people. Work systems, sports and leisure, health and safety should all embody ergonomics principles if well designed.

It is the applied science of equipment design intended to maximize productivity by reducing operator fatigue and discomfort. The field is also called biotechnology, human engineering, and human factors engineering. Ergonomic research is primarily performed by ergonomists who study human capabilities in relationship to their work demands. Information derived from ergonomists contributes to the design and evaluation of tasks, jobs, products, environments and systems in order to make them compatible with the needs, abilities and limitations of people.

Family systems therapy

Family systems therapy, also referred to as "family therapy" and "couple and family therapy", is a branch of psychotherapy related to relationship counseling that works with families and couples in intimate relationships to nurture change and development. It tends to view these in terms of the systems of interaction between family members.

It emphasizes family relationships as an important factor in psychological health. As such, family problems have been seen to arise as an emergent property of systemic interactions, rather than to be blamed on individual members. Marriage and Family Therapists (MFTs) are the most specifically trained in this type of psychotherapy.

Organizational psychology

Industrial and organizational psychology also known as "work psychology", "occupational psychology" or "personnel psychology" concerns the application of psychological theories, research methods, and intervention strategies to workplace issues. Industrial and organizational psychologists are interested in making organizations more productive while ensuring workers are able to lead physically and psychologically healthy lives. Relevant topics include personnel psychology, motivation and leadership, employee selection, training and development, organization development and guided change, organizational behavior, and job and family issues.

Perceptual control theory

Perceptual control theory (PCT) is a psychological theory of animal and human behavior originated by maverick scientist William T. Powers. In contrast with other theories of psychology and behavior, which assume that behavior is a function of perception — that perceptual inputs determine or cause behavior — PCT postulates that an organism's behavior is a means of controlling its perceptions. In contrast with engineering control theory, the reference variable for each negative feedback control loop in a control hierarchy is set from within the system (the organism), rather than by an external agent changing the setpoint of the controller.[6] PCT also applies to nonliving autonomic systems.[7]

Psychosynthesis

Psychosynthesis is an original approach to psychology that was developed by Roberto Assagioli. Psychosynthesis was not intended to be a school of thought or an exclusive method but many conferences and publications had it as central theme and centers were formed in Italy and the USA in the 1960s.

Psychosynthesis departed from the empirical foundations of psychology in that it studied a person as a personality and a soul but Assagioli continued to insist that it was scientific. Assagioli developed therapeutic methods other than what was found in psychoanalysis. Although the unconscious is an important part of the theory, Assagioli was careful to maintain a balance with rational, conscious therapeutical work.

See also

Related fields

- Behavior settings
- Chaos theory
- Communication theory
- Community psychology
- Complex systems
- Constructivist epistemology
- Critical theory
- Environmental psychology
- Living systems theory
- New Cybernetics
- Neuro cybernetics
- Process Oriented Psychology
- Social psychology
- Sociotechnical systems theory
- Somatic psychology

Related scientists

- William Ross Ashby
- Gregory Bateson
- John Bowlby
- Urie Bronfenbrenner
- Fritjof Capra
- Donald deAvila Jackson
- Thomas Homer-Dixon
- Fred Emery
- Clare W. Graves
- Pim Haselager
- Bradford Keeney
- Kurt Lewin
- Humberto Maturana
- Enid Mumford
- Talcott Parsons
- Gordon Pask
- William T. Powers
- Anatol Rapoport
- Jeffrey Satinover

- Einar Thorsrud
- Eric Trist
- Stuart Umpleby
- Francisco Varela
- Ludwig von Bertalanffy
- Lev Vygotsky
- Ken Wilber
- Michael White
- Alexander Zelitchenko

Related concepts

- Awareness
- Child development
- Conatus
- Conceptual system
- Connectionism
- Consciousness
- Cultural system
- Embodied Embedded Cognition
- Equifinality
- Homeodynamics
- Human ecosystem
- Model of hierarchical complexity
- Postcognitivism
- Self control
- Social network
- Systems intelligence

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External links

- Association for Process Psychology [13]

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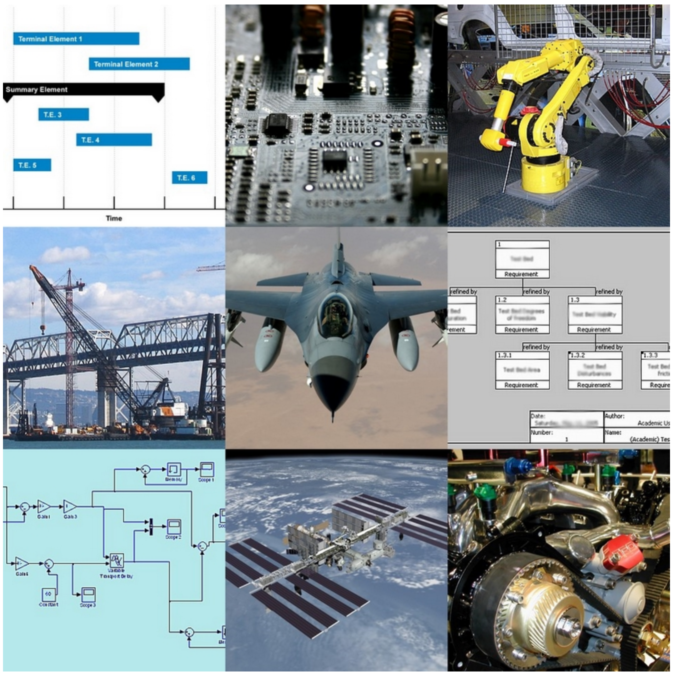
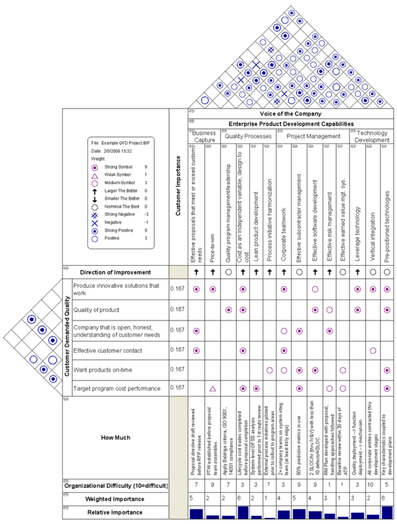
Systems engineering

Systems engineering is an interdisciplinary field of engineering that focuses on how complex engineering projects should be designed and managed. Issues such as logistics, the coordination of different teams, and automatic control of machinery become more difficult when dealing with large, complex projects. Systems engineering deals with work-processes and tools to handle such projects, and it overlaps with both technical and human-centered disciplines such as control engineering and project management.



Systems engineering techniques are used in complex projects: spacecraft design, computer chip design, robotics, software integration, and bridge building. Systems engineering uses a host of tools that include modeling and simulation, requirements analysis and scheduling to manage complexity.

History



QFD House of Quality for Enterprise Product Development Processes

The term *systems engineering* can be traced back to Bell Telephone Laboratories in the 1940s.[1] The need to identify and manipulate the properties of a system as a whole, which in complex engineering projects may greatly differ from the sum of the parts' properties, motivated the Department of Defense, NASA, and other industries to apply the discipline.[2]

When it was no longer possible to rely on design evolution to improve upon a system and the existing tools were not sufficient to meet growing demands, new methods began to be developed that addressed the complexity directly.[3] The evolution of systems engineering, which continues to this day, comprises the development and identification of new methods and modeling techniques. These methods aid in better comprehension of engineering systems as they grow more complex. Popular tools that are often used in the Systems Engineering context were developed during these times, including USL, UML, QFD, and IDEF0.

In 1990, a professional society for systems engineering, the *National Council on Systems Engineering* (NCOSE), was founded by representatives from a number of US corporations and organizations. NCOSE was created to address

the need for improvements in systems engineering practices and education. As a result of growing involvement from systems engineers outside of the U.S., the name of the organization was changed to the International Council on Systems Engineering (INCOSE) in 1995.[4] Schools in several countries offer graduate programs in systems engineering, and continuing education options are also available for practicing engineers.[5]

Concept

Some definitions

"An interdisciplinary approach and means to enable the realization of successful systems"[6] — *INCOSE handbook, 2004.*

"System engineering is a robust approach to the design, creation, and operation of systems. In simple terms, the approach consists of identification and quantification of system goals, creation of alternative system design concepts, performance of design trades, selection and implementation of the best design, verification that the design is properly built and integrated, and post-implementation assessment of how well the system meets (or met) the goals."[7] — *NASA Systems engineering handbook, 1995.*

"The Art and Science of creating effective systems, using whole system, whole life principles" OR "The Art and Science of creating optimal solution systems to complex issues and problems"[8] — *Derek Hitchins, Prof. of Systems Engineering, former president of INCOSE (UK), 2007.*

"The concept from the engineering standpoint is the evolution of the engineering scientist, i.e., the scientific generalist who maintains a broad outlook. The method is that of the team approach. On large-scale-system problems, teams of scientists and engineers, generalists as well as specialists, exert their joint efforts to find a solution and physically realize it...The technique has been variously called the systems approach or the team development method."[9] — *Harry H. Goode & Robert E. Machol, 1957.*

"The Systems Engineering method recognizes each system is an integrated whole even though composed of diverse, specialized structures and sub-functions. It further recognizes that any system has a number of objectives and that the balance between them may differ widely from system to system. The methods seek to optimize the overall system functions according to the weighted objectives and to achieve maximum compatibility of its parts."[10] — *Systems Engineering Tools by Harold Chestnut, 1965.*

Systems Engineering signifies both an approach and, more recently, as a discipline in engineering. The aim of education in Systems Engineering is to simply formalize the approach and in doing so, identify new methods and research opportunities similar to the way it occurs in other fields of engineering. As an approach, Systems Engineering is holistic and interdisciplinary in flavor.

Origins and traditional scope

The traditional scope of engineering embraces the design, development, production and operation of physical systems, and systems engineering, as originally conceived, falls within this scope. "Systems engineering", in this sense of the term, refers to the distinctive set of concepts, methodologies, organizational structures (and so on) that have been developed to meet the challenges of engineering functional physical systems of unprecedented complexity. The Apollo program is a leading example of a systems engineering project.

The use of the term "systems engineering" has evolved over time to embrace a wider, more holistic concept of "systems" and of engineering processes. This evolution of the definition has been a subject of ongoing controversy [11], and the term continues to be applied to both the narrower and broader scope.

Holistic view

Systems Engineering focuses on analyzing and eliciting customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem, the system lifecycle. Oliver *et al.* claim that the systems engineering process can be decomposed into

- a *Systems Engineering Technical Process*, and
- a *Systems Engineering Management Process*.

Within Oliver's model, the goal of the Management Process is to organize the technical effort in the lifecycle, while the Technical Process includes *assessing available information*, *defining effectiveness measures*, to *create a behavior model*, *create a structure model*, *perform trade-off analysis*, and *create sequential build & test plan*.[11]

Depending on their application, although there are several models that are used in the industry, all of them aim to identify the relation between the various stages mentioned above and incorporate feedback. Examples of such models include the Waterfall model and the VEE model.[12]

Interdisciplinary field

System development often requires contribution from diverse technical disciplines.[13] By providing a systems (holistic) view of the development effort, systems engineering helps meld all the technical contributors into a unified team effort, forming a structured development process that proceeds from concept to production to operation and, in some cases, to termination and disposal.

This perspective is often replicated in educational programs in that Systems Engineering courses are taught by faculty from other engineering departments which, in effect, helps create an interdisciplinary environment.[14] [15]

Managing complexity

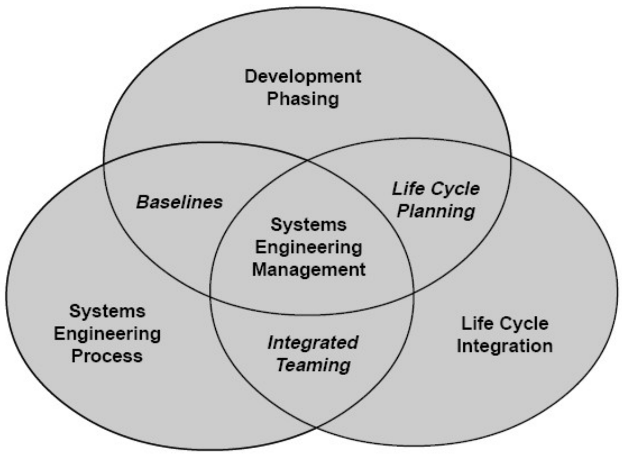
The need for systems engineering arose with the increase in complexity of systems and projects. When speaking in this context, complexity incorporates not only engineering systems, but also the logical human organization of data. At the same time, a system can become more complex due to an increase in size as well as with an increase in the amount of data, variables, or the number of fields that are involved in the design. The International Space Station is an example of such a system.

The development of smarter control algorithms, microprocessor design, and analysis of environmental systems also come within the purview of systems engineering. Systems engineering encourages the use of tools and methods to better comprehend and manage complexity in systems. Some examples of these tools can be seen here:[16]

- *Modeling and Simulation*,
- *Optimization*,
- *System dynamics*,
- *Systems analysis*,
- *Statistical analysis*,
- *Reliability analysis*, and
- *Decision making*

Taking an interdisciplinary approach to engineering systems is inherently complex since the behavior of and interaction among system components is not always immediately well defined or understood. Defining and characterizing such systems and subsystems and the interactions among them is one of the goals of systems engineering. In doing so, the gap that exists between informal requirements from users, operators, marketing organizations, and technical specifications is successfully bridged.

Scope



The scope of Systems Engineering activities[17]

One way to understand the motivation behind systems engineering is to see it as a method, or practice, to identify and improve common rules that exist within a wide variety of systems. Keeping this in mind, the principles of Systems Engineering — holism, emergent behavior, boundary, et al. — can be applied to any system, complex or otherwise, provided systems thinking is employed at all levels.[18] Besides defense and aerospace, many information and technology based companies, software development firms, and industries in the field of electronics & communications require Systems engineers as part of their team.[19]

An analysis by the INCOSE Systems Engineering center of excellence (SECOE) indicates that optimal effort spent on Systems Engineering is about 15-20% of the total project effort.[20] At the same time, studies have shown that Systems Engineering essentially leads to reduction in costs among other benefits.[20] However, no quantitative survey at a larger scale encompassing a wide variety of industries has been conducted until recently. Such studies are underway to determine the effectiveness and quantify the benefits of Systems engineering.[21] [22]

Systems engineering encourages the use of modeling and simulation to validate assumptions or theories on systems and the interactions within them.[23] [24]

Use of methods that allow early detection of possible failures, in Safety engineering, are integrated into the design process. At the same time, decisions made at the beginning of a project whose consequences are not clearly understood can have enormous implications later in the life of a system, and it is the task of the modern systems engineer to explore these issues and make critical decisions. There is no method which guarantees that decisions made today will still be valid when a system goes into service years or decades after it is first conceived but there are techniques to support the process of systems engineering. Examples include the use of soft systems methodology, Jay Wright Forrester's System dynamics method and the Unified Modeling Language (UML), each of which are currently being explored, evaluated and developed to support the engineering decision making process.

Education

Education in systems engineering is often seen as an extension to the regular engineering courses,[25] reflecting the industry attitude that engineering students need a foundational background in one of the traditional engineering disciplines (e.g. mechanical engineering, industrial engineering, computer science, electrical engineering) plus practical, real-world experience in order to be effective as systems engineers. Undergraduate university programs in systems engineering are rare.

INCOSE maintains a continuously updated Directory of Systems Engineering Academic Programs worldwide.[5] As of 2006, there are about 75 institutions in United States that offer 130 undergraduate and graduate programs in systems engineering. Education in systems engineering can be taken as *SE-centric* or *Domain-centric*.

- *SE-centric* programs treat systems engineering as a separate discipline and all the courses are taught focusing on systems engineering practice and techniques.
- *Domain-centric* programs offer systems engineering as an option that can be exercised with another major field in engineering.

Both these patterns cater to educate the systems engineer who is able to oversee interdisciplinary projects with the depth required of a core-engineer.[26]

Systems engineering topics

Systems engineering tools are strategies, procedures, and techniques that aid in performing systems engineering on a project or product. The purpose of these tools vary from database management, graphical browsing, simulation, and reasoning, to document production, neutral import/export and more.[27]

System

There are many definitions of what a system is in the field of systems engineering. Below are a few authoritative definitions:

- ANSI/EIA-632-1999: "An aggregation of end products and enabling products to achieve a given purpose."[28]
- IEEE Std 1220-1998: "A set or arrangement of elements and processes that are related and whose behavior satisfies customer/operational needs and provides for life cycle sustainment of the products."[29]
- ISO/IEC 15288:2008: "A combination of interacting elements organized to achieve one or more stated purposes."[30]
- NASA Systems Engineering Handbook: "(1) The combination of elements that function together to produce the capability to meet a need. The elements include all hardware, software, equipment, facilities, personnel, processes, and procedures needed for this purpose. (2) The end product (which performs operational functions) and enabling products (which provide life-cycle support services to the operational end products) that make up a system."[31]
- INCOSE Systems Engineering Handbook: "homogeneous entity that exhibits predefined behavior in the real world and is composed of heterogeneous parts that do not individually exhibit that behavior and an integrated configuration of components and/or subsystems."[32]
- INCOSE: "A system is a construct or collection of different elements that together produce results not obtainable by the elements alone. The elements, or parts, can include people, hardware, software, facilities, policies, and documents; that is, all things required to produce systems-level results. The results include system level qualities, properties, characteristics, functions, behavior and performance. The value added by the system as a whole, beyond that contributed independently by the parts, is primarily created by the relationship among the parts; that is, how they are interconnected."[33]

The systems engineering process

Depending on their application, tools are used for various stages of the systems engineering process:[17]

Using models

Models play important and diverse roles in systems engineering. A model can be defined in several ways, including:[34]

- An abstraction of reality designed to answer specific questions about the real world
- An imitation, analogue, or representation of a real world process or structure; or
- A conceptual, mathematical, or physical tool to assist a decision maker.

Together, these definitions are broad enough to encompass physical engineering models used in the verification of a system design, as well as schematic models like a functional flow block diagram and mathematical (i.e., quantitative) models used in the trade study process. This section focuses on the last.[34]

The main reason for using mathematical models and diagrams in trade studies is to provide estimates of system effectiveness, performance or technical attributes, and cost from a set of known or estimable quantities. Typically, a collection of separate models is needed to provide all of these outcome variables. The heart of any mathematical model is a set of meaningful quantitative relationships among its inputs and outputs. These relationships can be as simple as adding up constituent quantities to obtain a total, or as complex as a set of differential equations describing the trajectory of a spacecraft in a gravitational field. Ideally, the relationships express causality, not just correlation.[34]

Tools for graphic representations

Initially, when the primary purpose of a systems engineer is to comprehend a complex problem, graphic representations of a system are used to communicate a system's functional and data requirements.[35] Common graphical representations include:

- Functional Flow Block Diagram (FFBD)
- Data Flow Diagram (DFD)
- N2 (N-Squared) Chart
- IDEF0 Diagram
- UML Use case diagram
- UML Sequence diagram
- USL Function Maps and Type Maps.
- Enterprise Architecture frameworks, like TOGAF, MODAF, Zachman Frameworks etc.

A graphical representation relates the various subsystems or parts of a system through functions, data, or interfaces. Any or each of the above methods are used in an industry based on its requirements. For instance, the N2 chart may be used where interfaces between systems is important. Part of the design phase is to create structural and behavioral models of the system.

Once the requirements are understood, it is now the responsibility of a Systems engineer to refine them, and to determine, along with other engineers, the best technology for a job. At this point starting with a trade study, systems engineering encourages the use of weighted choices to determine the best option. A decision matrix, or Pugh method, is one way (QFD is another) to make this choice while considering all criteria that are important. The trade study in turn informs the design which again affects the graphic representations of the system (without changing the requirements). In an SE process, this stage represents the iterative step that is carried out until a feasible solution is found. A decision matrix is often populated using techniques such as statistical analysis, reliability analysis, system dynamics (feedback control), and optimization methods.

At times a systems engineer must assess the existence of feasible solutions, and rarely will customer inputs arrive at only one. Some customer requirements will produce no feasible solution. Constraints must be traded to find one or more feasible solutions. The customers' wants become the most valuable input to such a trade and cannot be assumed. Those wants/desires may only be discovered by the customer once the customer finds that he has overconstrained the problem. Most commonly, many feasible solutions can be found, and a sufficient set of constraints must be defined to produce an optimal solution. This situation is at times advantageous because one can present an opportunity to improve the design towards one or many ends, such as cost or schedule. Various modeling methods can be used to solve the problem including constraints and a cost function.

Systems Modeling Language (SysML), a modeling language used for systems engineering applications, supports the specification, analysis, design, verification and validation of a broad range of complex systems.[36]

Universal Systems Language (USL) is a systems oriented object modeling language with executable (computer independent) semantics for defining complex systems, including software.[37]

Closely related fields

Many related fields may be considered tightly coupled to systems engineering. These areas have contributed to the development of systems engineering as a distinct entity.

Cognitive systems engineering

> Cognitive systems engineering (CSE) is a specific approach to the description and analysis of human-machine systems or sociotechnical systems.[38] The three main themes of CSE are how humans cope with complexity, how work is accomplished by the use of artefacts, and how human-machine systems and socio-technical systems can be described as joint cognitive systems. CSE has since its beginning become a recognised scientific discipline, sometimes also referred to as Cognitive Engineering. The concept of a Joint Cognitive System (JCS) has in particular become widely used as a way of understanding how complex socio-technical systems can be described with varying degrees of resolution. The experience with CSE has been described in two books that summarises the field after more than 20 years of work, namely[39] and [40] .

Configuration Management

> Like Systems Engineering, Configuration Management as practiced in the defence and aerospace industry is a broad systems-level practice. The field parallels the taskings of Systems Engineering; where Systems Engineering deals with requirements development, allocation to development items and verification, Configuration Management deals with requirements capture, traceability to the development item, and audit of development item to ensure that it has achieved the desired functionality that Systems Engineering and/or Test and Verification Engineering have proven out through objective testing.

Control engineering

> Control engineering and its design and implementation of control systems, used extensively in nearly every industry, is a large sub-field of Systems Engineering. The cruise control on an automobile and the guidance system for a ballistic missile are two examples. Control systems theory is an active field of applied mathematics involving the investigation of solution spaces and the development of new methods for the analysis of the control process.

Industrial engineering

> Industrial engineering is a branch of engineering that concerns the development, improvement, implementation and evaluation of integrated systems of people, money, knowledge, information, equipment, energy, material and process. Industrial engineering draws upon the principles and methods of engineering analysis and synthesis, as well as mathematical, physical and social sciences together with the principles and methods of engineering analysis and design to specify, predict and evaluate the results to be obtained from such systems.

Interface design

Interface design and its specification are concerned with assuring that the pieces of a system connect and inter-operate with other parts of the system and with external systems as necessary. Interface design also includes assuring that system interfaces be able to accept new features, including mechanical, electrical and logical interfaces, including reserved wires, plug-space, command codes and bits in communication protocols. This is known as extensibility. Human-Computer Interaction (HCI) or Human-Machine Interface (HMI) is another aspect of interface design, and is a critical aspect of modern Systems Engineering. Systems engineering principles are applied in the design of network protocols for local-area networks and wide-area networks.

Operations research

Operations research supports systems engineering. The tools of operations research are used in systems analysis, decision making, and trade studies. Several schools teach SE courses within the operations research or industrial engineering department, highlighting the role systems engineering plays in complex projects. operations research, briefly, is concerned with the optimization of a process under multiple constraints.[41]

Reliability engineering

Reliability engineering is the discipline of ensuring a system will meet the customer's expectations for reliability throughout its life; i.e. it will not fail more frequently than expected. Reliability engineering applies to all aspects of the system. It is closely associated with maintainability, availability and logistics engineering. Reliability engineering is always a critical component of safety engineering, as in failure modes and effects analysis (FMEA) and hazard fault tree analysis, and of security engineering. Reliability engineering relies heavily on statistics, probability theory and reliability theory for its tools and processes.

Performance engineering

Performance engineering is the discipline of ensuring a system will meet the customer's expectations for performance throughout its life. Performance is usually defined as the speed with which a certain operation is executed or the capability of executing a number of such operations in a unit of time. Performance may be degraded when an operations queue to be executed is throttled when the capacity is of the system is limited. For example, the performance of a packet-switched network would be characterised by the end-to-end packet transit delay or the number of packets switched within an hour. The design of high-performance systems makes use of analytical or simulation modeling, whereas the delivery of high-performance implementation involves thorough performance testing. Performance engineering relies heavily on statistics, queuing theory and probability theory for its tools and processes.

Program management and project management.

Program management (or programme management) has many similarities with systems engineering, but has broader-based origins than the engineering ones of systems engineering. Project management is also closely related to both program management and systems engineering.

Safety engineering

The techniques of safety engineering may be applied by non-specialist engineers in designing complex systems to minimize the probability of safety-critical failures. The "System Safety Engineering" function helps to identify "safety hazards" in emerging designs, and may assist with techniques to "mitigate" the effects of (potentially) hazardous conditions that cannot be designed out of systems.

Security engineering

Security engineering can be viewed as an interdisciplinary field that integrates the community of practice for control systems design, reliability, safety and systems engineering. It may involve such sub-specialties as authentication of system users, system targets and others: people, objects and processes.

Software engineering

From its beginnings Software engineering has helped shape modern Systems Engineering practice. The techniques used in the handling of complexes of large software-intensive systems has had a major effect on the shaping and reshaping of the tools, methods and processes of SE.

See also

Lists

- List of production topics
- List of systems engineers
- List of types of systems engineering
- List of systems engineering at universities

Topics

- Management cybernetics
- Enterprise systems engineering
- System of systems engineering (SoSE)

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Sociotechnical systems theory

Sociotechnical systems (**STS**) in organizational development is an approach to complex organizational work design that recognizes the interaction between people and technology in workplaces. The term also refers to the interaction between society's complex infrastructures and human behaviour. In this sense, society itself, and most of its substructures, are complex sociotechnical systems. The term sociotechnical systems was coined in the 1960s by Eric Trist and Fred Emery, who were working as consultants at the Tavistock Institute in London.

Sociotechnical systems theory is theory about the social aspects of people and society and technical aspects of machines and technology. Sociotechnical refers to the interrelatedness of *social* and *technical* aspects of an organisation. Sociotechnical theory therefore is about *joint optimization*, with a shared emphasis on achievement of both excellence in technical performance and quality in people's work lives. Sociotechnical theory, as distinct from sociotechnical systems, proposes a number of different ways of achieving joint optimisation. They are usually based on designing different kinds of organisation, ones in which the relationships between socio and technical elements lead to the emergence of productivity and wellbeing.

Overview

Sociotechnical refers to the interrelatedness of *social* and *technical* aspects of an organization. Sociotechnical theory is founded on two main principles:

- One is that the interaction of social and technical factors creates the conditions for successful (or unsuccessful) organizational performance. This interaction is comprised partly of linear ‘cause and effect’ relationships (the relationships that are normally ‘designed’) and partly from ‘non-linear’, complex, even unpredictable relationships (the good or bad relationships that are often unexpected). Whether designed or not, both types of interaction occur when socio and technical elements are put to work.
- The corollary of this, and the second of the two main principles, is that optimisation of each aspect alone (socio or technical) tends to increase not only the quantity of unpredictable, ‘un-designed’ relationships, but those relationships that are injurious to the system’s performance.

Therefore sociotechnical theory is about *joint optimisation*. Sociotechnical theory, as distinct from sociotechnical systems, proposes a number of different ways of achieving joint optimisation. They are usually based on designing different kinds of organization, ones in which the relationships between socio and technical elements lead to the emergence of productivity and wellbeing, rather than the all too often case of new technology failing to meet the expectations of designers and users alike.

The scientific literature shows terms like *sociotechnical* all one word, or *sociotechnical* with a hyphen, *sociotechnical theory*, *sociotechnical system* and *sociotechnical systems theory*. All of these terms appear ubiquitously but their actual meanings often remain unclear. The key term 'sociotechnical' is something of a buzzword and its varied usage can be unpicked. What can be said about it, though, is that it is most often used to simply, and quite correctly, describe any kind of organization that is composed of people and technology. But, predictably, there is more to it than that.

Principles

Some of the central principles of sociotechnical theory were elaborated in a seminal paper by Eric Trist and Ken Bamforth in 1951. This is an interesting case study which, like most of the work in sociotechnical theory, is focused on a form of ‘production system’ expressive of the era and the contemporary technological systems it contained. The study was based on the paradoxical observation that despite improved technology, productivity was falling, and that despite better pay and amenities, absenteeism was increasing. This particular rational organisation had become irrational. The cause of the problem was hypothesized to be the adoption of a new form of production technology

which had created the need for a bureaucratic form of organization (rather like classic C2). In this specific example, technology brought with it a retrograde step in organizational design terms. The analysis that followed introduced the terms ‘socio’ and ‘technical’ and elaborated on many of the core principles that sociotechnical theory subsequently became.

Responsible autonomy

Sociotechnical theory was pioneering for its shift in emphasis, a shift towards considering teams or groups as the primary unit of analysis and not the individual. Sociotechnical theory pays particular attention to internal supervision and leadership at the level of the ‘group’ and refers to it as ‘responsible autonomy’[1] The overriding point seems to be that having the simple ability of individual team members being able to perform their function is not the only predictor of combat effectiveness. There are a range of issues in team cohesion research, for example, that are answered by having the regulation and leadership internal to a group or team [2] .

These, and other factors, play an integral and parallel role in ensuring successful teamwork which sociotechnical theory exploits. The idea of semi-autonomous groups conveys a number of further advantages. Not least among these, especially in hazardous environments, is the often felt need on the part of people in the organisation for a role in a small primary group. It is argued that such a need arises in cases where the means for effective communication are often somewhat limited. As Carvalho [3] states, this is because “…operators use verbal exchanges to produce continuous, redundant and recursive interactions to successfully construct and maintain individual and mutual awareness…”. The immediacy and proximity of trusted team members makes it possible for this to occur. The co-evolution of technology and organizations brings with it an expanding array of new possibilities for novel interaction. Responsible autonomy could become more distributed along with the team(s) themselves.

The key to responsible autonomy seems to be to design an organization possessing the characteristics of small groups whilst preventing the ‘silo-thinking’ and ‘stovepipe’ neologisms of contemporary management theory. In order to preserve “…intact the loyalties on which the small group [depend]…the system as a whole [needs to contain] its bad in a way that [does] not destroy its good”.[1] In practice [4] this requires groups to be responsible for their own internal regulation and supervision, with the primary task of relating the group to the wider system falling explicitly to a group leader. This principle, therefore, describes a strategy for removing more traditional command hierarchies.

Adaptability

Carvajal [5] states that “the rate at which uncertainty overwhelms an organisation is related more to its internal structure than to the amount of environmental uncertainty”. Sitter in 1997 offered two solutions for organisations confronted, like the military, with an environment of increased (and increasing) complexity: “The first option is to restore the fit with the external complexity by an increasing internal complexity. ...This usually means the creation of more staff functions or the enlargement of staff-functions and/or the investment in vertical information systems”. [6] . Vertical information systems are often confused for 'network enabled capability' systems (NEC) but an important distinction needs to be made, which Sitter et al. propose as their second option: “…the organisation tries to deal with the external complexity by ‘reducing’ the internal control and coordination needs. ...This option might be called the strategy of ‘simple organisations and complex jobs’”. This all contributes to a number of unique advantages. Firstly is the issue of ‘human redundancy’[7] in which “groups of this kind were free to set their own targets, so that aspiration levels with respect to production could be adjusted to the age and stamina of the individuals concerned”.[1] Human redundancy speaks towards the flexibility, ubiquity and pervasiveness of resources within NEC.

The second issue is that of complexity. Complexity lies at the heart of many organisational contexts (there are numerous organizational paradigms that struggle to cope with it). Trist and Bamforth (1951) could have been writing about these with the following passage: “A very large variety of unfavourable and changing environmental conditions is encountered ... many of which are impossible to predict. Others, though predictable, are impossible to

alter."[8]

Many type of organisations are clearly motivated by the appealing 'industrial age', rational principles of 'factory production', a particular approach to dealing with complexity: "In the factory a comparatively high degree of control can be exercised over the complex and moving 'figure' of a production sequence, since it is possible to maintain the 'ground' in a comparatively passive and constant state".[8] On the other hand, many activities are constantly faced with the possibility of "untoward activity in the 'ground'" of the 'figure-ground' relationship"[8] The central problem, one that appears to be at the nub of many problems that 'classic' organisations have with complexity, is that "The instability of the 'ground' limits the applicability […] of methods derived from the factory".[8]

In Classic organisations problems with the moving 'figure' and moving 'ground' often become magnified through a much larger social space, one in which there is a far greater extent of hierarchical task interdependence.[8] For this reason, the semi-autonomous group, and its ability to make a much more fine grained response to the 'ground' situation, can be regarded as 'agile'. Added to which, local problems that do arise need not propagate throughout the entire system (to affect the workload and quality of work of many others) because a complex organization doing simple tasks has been replaced by a simpler organization doing more complex tasks. The agility and internal regulation of the group allows problems to be solved locally without propagation through a larger social space, thus increasing tempo.

Whole tasks

Another concept in sociotechnical theory is the 'whole task'. A whole task "has the advantage of placing responsibility for the […] task squarely on the shoulders of a single, small, face-to-face group which experiences the entire cycle of operations within the compass of its membership."[1] The Sociotechnical embodiment of this principle is the notion of minimal critical specification. This principle states that, "While it may be necessary to be quite precise about what has to be done, it is rarely necessary to be precise about how it is done" [9] . This is no more illustrated by the antithetical example of 'working to rule' and the virtual collapse of any system that is subject to the intentional withdrawal of human adaptation to situations and contexts.

The key factor in minimally critically specifying tasks is the responsible autonomy of the group to decide, based on local conditions, how best to undertake the task in a flexible adaptive manner. This principle is isomorphic with ideas like Effects Based Operations (EBO). EBO asks the question of what goal is it that we want to achieve, what objective is it that we need to reach rather than what tasks have to be undertaken, when and how. The EBO concept enables the managers to "…manipulate and decompose high level effects. They must then assign lesser effects as objectives for subordinates to achieve. The intention is that subordinates' actions will cumulatively achieve the overall effects desired" [10] . In other words, the focus shifts from being a scriptwriter for tasks to instead being a designer of behaviours. In some cases this can make the task of the manager significantly less arduous.

Meaningfulness of tasks

Effects Based Operations and the notion of a 'whole task', combined with adaptability and responsible autonomy, have additional advantages for those at work in the organization. This is because "for each participant the task has total significance and dynamic closure"[1] as well as the requirement to deploy a multiplicity of skills and to have the responsible autonomy in order to select when and how to do so. This is clearly hinting at a relaxation of the myriad control mechanisms found in the more classically designed organizations like.

Greater interdependance (through diffuse processes such as globalisation) also bring with them an issue of size, in which "the scale of a task transcends the limits of simple spatio-temporal structure. By this is meant conditions under which those concerned can complete a job in one place at one time, i.e., the situation of the face-to-face, or singular group". In other words, in classic organisations the 'wholeness' of a task is often diminished by multiple group integration and spatiotemporal disintegration. [11] . The group based form of organization design proposed by sociotechnical theory combined with new technological possibilities (such as the internet) provide a response to this

often forgotten issue, one that contributes significantly to joint optimisation.

Topics in sociotechnical systems theory

Sociotechnical system

A sociotechnical system is the term usually given to any instantiation of socio and technical elements engaged in goal directed behaviour. Sociotechnical systems are a particular expression of sociotechnical theory, although they are not necessarily one and the same thing. Sociotechnical systems theory is a mixture of sociotechnical theory, joint optimisation and so forth and general systems theory. The term sociotechnical system recognises that organisations have boundaries and that transactions occur within the system (and its sub-systems) and between the wider context and dynamics of the environment. It is an extension of Sociotechnical Theory which provides a richer descriptive and conceptual language for describing, analysing and designing organisations. A Sociotechnical System, therefore, often describes a 'thing' (an interlinked, systems based mixture of people, technology and their environment).

Socio technical systems approach

Socio technical systems in organizational development is the term for an approach to complex organizational work design that recognizes the interaction between people and technology in workplaces. The term also refers to the interaction between society's complex infrastructures and human behavior. In this sense, society itself, and most of its sub-structures, are complex socio technical systems.

Job enrichment

Job enrichment in organizational development, human resources management, and organizational behavior, is the process of giving the employee a wider and higher level scope of responsibilitiy with increased decision making authority. This is the opposite of job enlargement, which simply would not involve greater authority. Instead, it will only have an increased number of duties.[12]

Job enlargement

Job enlargement means increasing the scope of a job through extending the range of its job duties and responsibilities. This contradicts the principles of specialisation and the division of labour whereby work is divided into small units, each of which is performed repetitively by an individual worker. Some motivational theories suggest that the boredom and alienation caused by the division of labour can actually cause efficiency to fall.

Job rotation

Job rotation is an approach to management development, where an individual is moved through a schedule of assignments designed to give him or her a breadth of exposure to the entire operation. Job rotation is also practiced to allow qualified employees to gain more insights into the processes of a company and to increase job satisfaction through job variation. The term job rotation can also mean the scheduled exchange of persons in offices, especially in public offices, prior to the end of incumbency or the legislative period. This has been practiced by the German green party for some time but has been discontinued

Motivation

Motivation in psychology refers to the initiation, direction, intensity and persistence of behavior.[13] Motivation is a temporal and dynamic state that should not be confused with personality or emotion. Motivation is having the desire and willingness to do something. A motivated person can be reaching for a long-term goal such as becoming a professional writer or a more short-term goal like learning how to spell a particular word. Personality invariably refers to more or less permanent characteristics of an individual's state of being (e.g., shy,extrovert, conscientious. As opposed to motivation, emotion refers to temporal states that do not immediately link to behavior (e.g., anger, grief, happiness).

Process improvement

Process improvement in organizational development is a series of actions taken to identify, analyze and improve existing processes within an organization to meet new goals and objectives. These actions often follow a specific methodology or strategy to create successful results.

Task analysis

Task analysis is the analysis of how a task is accomplished, including a detailed description of both manual and mental activities, task and element durations, task frequency, task allocation, task complexity, environmental conditions, necessary clothing and equipment, and any other unique factors involved in or required for one or more people to perform a given task. This information can then be used for many purposes, such as personnel selection and training, tool or equipment design, procedure design (e.g., design of checklists or decision support systems) and automation.

Work design

Work design or job design in organizational development is the application of sociotechnical systems principles and techniques to the humanization of work. The aims of work design to improved job satisfaction, to improved through-put, to improved quality and to reduced employee problems, e.g., grievances, absenteeism.

See also

- List of management topics
- Complex systems
- Cybernetics
- Feedback
- Human factors
- Social network
- Sociology
- Systems theory
- Systems science

Further reading

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- STS Roundtable [16] , an international not-for-profit association of professional and scholarly practitioners of Sociotechnical Systems Theory
- IEEE 1st Workshop on Socio-Technical Aspects of Mashups [17]
- http://www.fsc.yorku.ca/york/istheory/wiki/index.php/Socio-technical_theory
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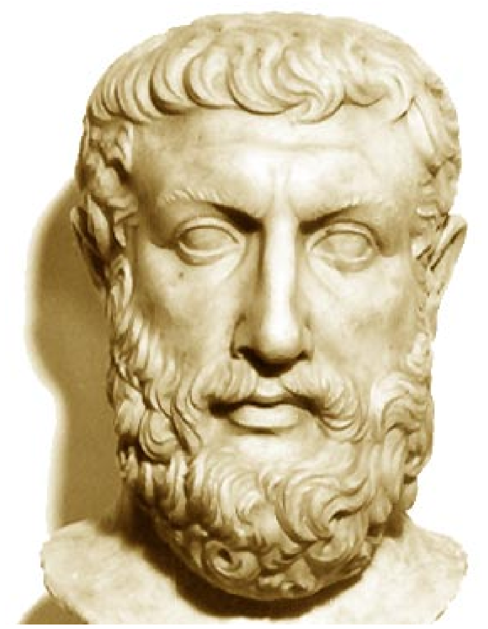
Ontology

Ontology (from the Greek ὄν, genitive ὄντος: *of being* (neuter participle of εἶναι: *to be*) and -λογία, -logia: *science*, *study*, *theory*) is the philosophical study of the nature of being, existence or reality in general, as well as the basic categories of being and their relations. Traditionally listed as a part of the major branch of philosophy known as metaphysics, ontology deals with questions concerning what entities exist or can be said to exist, and how such entities can be grouped, related within a hierarchy, and subdivided according to similarities and differences.


Parmenides was among the first to propose an ontological characterization of the fundamental nature of reality.

Overview

Students of the Greek philosopher Aristotle (384 BC – 322 BC) first used the word 'metaphysica' (literally "beyond the physical") to refer to what their teacher described as "the science of beings *qua* beings" - later known as ontology. *'Qua'* means 'in the capacity of'. Hence, ontology is inquiry into a being *in so much as* it is a being, or into beings insofar as they exist, and not insofar as, for instance, particular facts obtained about them or particular properties relating to them. More specifically, ontology concerns determining whether some *categories of being* are fundamental, and asks in what sense the items in those categories can be said to "be". For Aristotle there are four different ontological dimensions: i) according to the various categories or ways of addressing a being as such, ii) according to its truth or falsity (e.g. fake gold, counterfeit money), iii) whether it exists in and of itself or simply 'comes along' by accident, and iv) according to its potency, movement (energy) or finished presence (*Metaphysics* Book Theta).

Some philosophers, notably of the Platonic school, contend that all nouns (including abstract nouns) refer to existent entities. Other philosophers contend that nouns do not always name entities, but that some provide a kind of shorthand for reference to a collection of either objects or events. In this latter view, *mind*, instead of referring to an entity, refers to a collection of *mental events* experienced by a person; *society* refers to a collection of persons with some shared characteristics, and *geometry* refers to a collection of a specific kind of intellectual activity.[1] Between these poles of realism and nominalism, there are also a variety of other positions; but any ontology must give an account of which words refer to entities, which do not, why, and what categories result. When one applies this process to nouns such as *electrons*, *energy*, *contract*, *happiness*, *space*, *time*, *truth*, *causality*, and *God*, ontology becomes fundamental to many branches of philosophy.

Some fundamental questions

Principal questions of ontology are "What can be said to exist?", "Into what categories, if any, can we sort existing things?", "What are the meanings of being?", "What are the various modes of being of entities?". Various philosophers have provided different answers to these questions.

One common approach is to divide the extant entities into groups called categories. Of course, such lists of categories differ widely from one another, and it is through the co-ordination of different categorial schemes that ontology relates to such fields as library science and artificial intelligence. Such an understanding of ontological categories, however, is merely taxonomic, classificatory. The categories are, properly speaking, the ways in which a being can be addressed simply as a being, such as what it is (its 'whatness', quidditas or essence), how it is (its 'howness' or qualitativeness), how much it is (quantitativeness), where it is, its relatedness to other beings, etc.

Further examples of ontological questions include:

- What is existence, i.e. what does it mean for a being to be?
- Is existence a property?
- Is existence a genus or general class that is simply divided up by specific differences?
- Which entities, if any, are fundamental? Are all entities objects?
- How do the properties of an object relate to the object itself?
- What features are the essential, as opposed to merely accidental, attributes of a given object?
- How many levels of existence or ontological levels are there? And what constitutes a 'level'?
- What is a physical object?
- Can one give an account of what it means to say that a physical object exists?
- Can one give an account of what it means to say that a non-physical entity exists?
- What constitutes the *identity* of an object?
- When does an object go *out* of existence, as opposed to merely *changing*?
- Do beings exist other than in the modes of objectivity and subjectivity, i.e. is the subject/object split of modern philosophy inevitable?

Concepts

Quintessential ontological concepts include:

- Universals and Particulars
- Substance and Accident
- Abstract and Concrete objects
- Essence and Existence
- Determinism and Indeterminism

History of ontology

Etymology

While the etymology is Greek, the oldest extant record of the word itself is the Latin form *ontologia*, which appeared in 1606, in the work *Ogdoas Scholastica* by Jacob Lorhard (*Lorhardus*) and in 1613 in the *Lexicon philosophicum* by Rudolf Göckel (*Goclenius*).

The first occurrence in English of "ontology" as recorded by the OED (Oxford English Dictionary, second edition, 1989) appears in Bailey's dictionary of 1721, which defines ontology as ‘an Account of being in the Abstract’ - though, of course, such an entry indicates the term was already in use at the time. It is likely the word was first used in its Latin form by philosophers based on the Latin roots, which themselves are based on the Greek. The current on-line edition of the OED (Draft Revision September 2008) gives as first occurrence in English a work by Gideon

Harvey (1636/7-1702): *Archelogia philosophica nova; or, New principles of Philosophy. Containing Philosophy in general, Metaphysicks or Ontology, Dynamilogy or a Discourse of Power, Religio Philosophi or Natural Theology, Physicks or Natural philosophy* - London, Thomson, 1663.

Origins

Parmenides and Monism

Parmenides was among the first to propose an ontological characterization of the fundamental nature of reality. In his prologue or proem he describes two views of reality; initially that change is impossible, and therefore existence is eternal. Consequently our opinions about reality must often be false and deceitful. Most of western philosophy, and science - including the fundamental concepts of falsifiability and the conservation of energy - have emerged from this view. This posits that existence is what exists, and that there is nothing that does not exist. Hence, there can be neither void nor vacuum; and true reality can neither come into being nor vanish from existence. Rather, the entirety of creation is limitless, eternal, uniform, and immutable. Parmenides thus posits that change, as perceived in everyday experience, is illusory. Everything that we can apprehend is but one part of a single entity. This idea somewhat anticipates the modern concept of an ultimate grand unification theory that finally explains all of reality in terms of one inter-related sub-atomic reality which applies to everything.

Ontological pluralism

The opposite of eleatic monism is the pluralistic conception of Being. In the 5th century BC, Anaxagoras & Leucippus replaced [2] the reality of Being (unique and unchanging) with the Becoming and therefore by a more fundamental and elementary ontic plurality. This thesis originated in the Greek-ion world, stated in two different ways by Anaxagoras and by Leucippus. The first theory dealt with "seeds" (which Aristotle referred to as "homeomeries") of the various substances. The second was the atomistic theory,[3] which dealt with reality as based on the vacuum, the atoms and their intrinsic movement in it.

The materialist Atomism proposed by Leucippus was indeterminist, but then developed by Democritus in deterministic way. It was later (4th century BC) that the originary atomism was taken again as indeterministic by Epicurus. He confirmed the reality as composed of an infinity of indivisible, inchangeable corpuscles or atoms (*atomon*, lit. ‘uncuttable’), but he gives weight to characterize atoms while for Leucippus they are characterized by a "figure", an "order" and a "position" in the cosmos (Aristotle, *Metaphysics*, I , 4, 985). They are, besides, creating the whole with the intrinsic movement in the *vacuum*, producing the diverse flux of being. Their movement is influenced by the Parenklisis (Lucretius names it Clinamen) and that is determinated by the chance. These ideas foreshadowed our understanding of traditional physics until the nature of atoms was discovered in the 20th century..

Plato

Plato developed this distinction between true reality and illusion, in arguing that what is real are eternal and unchanging Forms or Ideas (a precursor to universals), of which things experienced in sensation are at best merely copies, and real only in so far as they copy (‘participate in’) such Forms. In general, Plato presumes that all nouns (e.g., ‘Beauty’) refer to real entities, whether sensible bodies or insensible Forms. Hence, in *The Sophist* Plato argues that Being is a Form in which all existent things participate and which they have in common (though it is unclear whether ‘Being’ is intended in the sense of existence, copula, or identity); and argues, against Parmenides, that Forms must exist not only of Being, but also of Negation and of non-Being (or Difference).

Aristotle

Ontology as an explicit discipline was inaugurated by Aristotle, in his Metaphysics, as the study of that which is common to all things which exist, and of the categorisation of the diverse senses in which things can and do exist. What exists, in so far as Aristotle concludes, are a plurality of independently existing substances – roughly, physical objects – on which the existence of other things, such as qualities or relations, may depend; and of which substances consist both of a form (e.g. a shape, pattern, or organisation), and of a matter formed (Hylomorphism). Disagreeing with Plato, who taught that frameworks or Forms have an existence of their own, Aristotle holds that universals do not have an existence over and above the particular things which instantiate them.-

Avicenna

Avicenna, an early Islamic Persian philosopher, is considered to be the first "philosopher of being" for placing ontology at the heart of philosophy. Influenced by the monotheism of Islam, he considered the study of being to be the heart of Islamic metaphysics. In Islamic philosophy, especially the Avicennan school, the concept of existence appears as a definate and clear concept to a much greater degree than in ancient Greek philosophy. Avicenna also distinguishes between necessity and contingency as a fundamental distinction between Pure Being, which is that of God and is very different from the Aristotelian understanding of being, and the existence of all that is other than Him. God is the Necessary Being (*wiijib al-wujúd*), while existents are contingent (*mumkin al-wujúd*) and hence rely in a fundamental way upon the Necessary Being, without which they would be literally nothing.[4]

Following Al-Farabi's lead, Avicenna initiated a full-fledged inquiry into the question of being, in which he distinguished between essence (*Mahiat*) and existence (*Wujud*). He argued that the fact of existence can not be inferred from or accounted for by the essence of existing things and that form and matter by themselves cannot interact and originate the movement of the universe or the progressive actualization of existing things. Existence must, therefore, be due to an agent-cause that necessitates, imparts, gives, or adds existence to an essence. To do so, the cause must be an existing thing and coexist with its effect.[5]

Avicenna was the first to view existence (*wujud*) as an accident that happens to the essence (*mahiyya*) and make a real distinction between essence and existence, and was also an early proponent of the concept of essentialism. Avicenna anticipated Frege and Bertrand Russell in "holding that existence is an accident of accidents" and also anticipated Alexius Meinong's "view about nonexistent objects."[6] He also provided early arguments for "a 'necessary being' as cause of all other existents."[7] . However, this aspect of ontology is not the most central to the distinction that Avicenna established between essence and existence. One cannot therefore make the claim that Avicenna was the proponent of the concept of essentialism *per se*, given that existence (*al-wujud*) when thought of in terms of necessity would ontologically translate into a notion of the *Necessary-Existent-due-to-Itself* (*wajib al-wujud bi-dhatihi*), which is without description or definition, and particularly without quiddity or essence (*la mahiyya lahu*). Consequently, Avicenna's ontology is 'existentialist' when accounting for being qua existence in terms of necessity (*wujub*), while it is 'essentialist' in terms of thinking about being qua existence (*wujud*) in terms of contingency qua possibility (*imkan*; or *mumkin al-wujud*: contingent being).[8]

Avicenna was also the first to argue that existence is not a predicate.[9] The idea of "essence precedes existence" is a concept which also dates back to Avicenna[10] and his school of Avicennism, and was further developed by Shahab al-Din Suhrawardi[11] and his Illuminationist philosophy. The opposite idea of "existence precedes essence" was thus developed in the works of Averroes[10] and Mulla Sadra as a reaction to this idea and is a key foundational concept of existentialism.[12] The ontological argument for the existence of God also originates from Avicenna.[9] [13]

Other ontological topics

Ontological and epistemological certainty

René Descartes, with "cogito ergo sum" or "I think, therefore I am", argued that "the self" is something that we can know exists with epistemological certainty. Descartes argued further that this knowledge could lead to a proof of the certainty of the existence of God, using the ontological argument that had been formulated first by Anselm of Canterbury.

Certainty about the existence of "the self" and "the other", however, came under increasing criticism in the 20th century. Sociological theorists, most notably George Herbert Mead and Erving Goffman, saw the Cartesian Other as a "Generalized Other", the imaginary audience that individuals use when thinking about the self. According to Mead, "we do not assume there is a self to begin with. Self is not presupposed as a stuff out of which the world arises. Rather the self arises in the world" [14] [15] The Cartesian Other was also used by Sigmund Freud, who saw the superego as an abstract regulatory force, and Émile Durkheim who viewed this as a psychologically manifested entity which represented God in society at large.

Body and environment, questioning the meaning of being

Schools of subjectivism, objectivism and relativism existed at various times in the 20th century, and the postmodernists and body philosophers tried to reframe all these questions in terms of bodies taking some specific action in an environment. This relied to a great degree on insights derived from scientific research into animals taking instinctive action in natural and artificial settings — as studied by biology, ecology, and cognitive science.

The processes by which bodies related to environments became of great concern, and the idea of being itself became difficult to really define. What did people mean when they said "A is B", "A must be B", "A was B"...? Some linguists advocated dropping the verb "to be" from the English language, leaving "E Prime", supposedly less prone to bad abstractions. Others, mostly philosophers, tried to dig into the word and its usage. Heidegger distinguished *human being* as *existence* from the being of things in the world. Heidegger proposes that our way of being human and the way the world is for us are cast historically through a fundamental ontological questioning. These fundamental ontological categories provide the basis for communication in an age: a horizon of unspoken and seemingly unquestionable background meanings, such as human beings understood unquestioningly as subjects and other entities understood unquestioningly as objects. Because these basic ontological meanings both generate and are regenerated in everyday interactions, the locus of our way of being in an historical epoch is the communicative event of language in use[14] . For Heidegger, however, communication in the *first* place is not among human beings, but language itself shapes up in response to questioning (the inexhaustible meaning of) being.[16] Even the focus of traditional ontology on the 'whatness' or 'quidditas' of beings in their substantial, standing presence can be shifted to pose the question of the 'whoness' of human being itself.[17]

Prominent ontologists

- Aristotle
- Aquinas
- Mario Bunge
- Franz Brentano
- Gilles Deleuze
- Hans-Georg Gadamer
- Nicolai Hartmann
- Martin Heidegger
- Heraclitus
- Georg Wilhelm Friedrich Hegel
- Edmund Husserl
- Immanuel Kant
- Gottfried Leibniz
- Leucippus
- Alexius Meinong
- Parmenides
- Plato
- Plotinus
- Proclus
- W. V. O. Quine
- Bertrand Russell
- Gilbert Ryle
- Jean-Paul Sartre
- Baruch Spinoza
- Alfred North Whitehead
- Ludwig Wittgenstein
- G. K. Chesterton

See also

- Applied Ontology
- Cosmology
- Epistemology
- Foundation ontology
- Geopolitical ontology
- Holism
- Mereology
- Meta-modeling
- Meta-ontology
- Metaphysics
- Modal logic
- Nihilism
- Ontological pluralism
- Ontophysical Pluralism
- Ontology (information science)
- Philosophy of science
- Philosophy of space and time
- Philosophy of mathematics
- Speculative Realism
- Physical ontology
- Quantum ontology
- Schema
- Solipsism
- Taxonomy
- Theology
- Upper ontology

External links

- Buffalo Ontology Site [18]
- John Symons, A Sketch of the History and Methodology of Ontology in the Analytic Tradition (DRAFT) [19]
- Theory and History of Ontology. Resource Guide for Philosophers [20]
- Stanford Encyclopedia Of Philosophy : Logic and Ontology [21]
- Free Open access book: Paolo Valore (ed), *Topics on General and Formal Ontology* [22].
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Notable Complexity Theoreticians

William Ross Ashby

W. Ross Ashby	
Born	6 September 1903 London, England
Died	15 November 1972 (aged 69)
Fields	Psychiatry, Cybernetics, Systems theory
Known for	Cybernetics, Law of Requisite Variety, Principle of Self-Organization
Influenced	Norbert Wiener, Ludwig von Bertalanffy, Herbert Simon, Stafford Beer and Stuart Kauffman

W. Ross Ashby (London, 6 September 1903 – 15 November 1972) was an English psychiatrist and a pioneer in cybernetics, the study of complex systems. His first name was not used: he was known as *Ross Ashby*.

His two books, *Design for a brain* and *An introduction to cybernetics*, were landmark works. They introduced exact, logical, thinking to the nascent discipline, and were highly influential.

Biography

William Ross Ashby was born in 1903 in London, where his father worked as assistant manager of an advertising agency.[1] From 1917 to 1921 William studied at the Edinburgh Academy in Scotland, and from 1921 at Sidney Sussex College, Cambridge, where he received his B.A. in 1924 and his M.B. and B.Ch. in 1928. From 1924 to 1928 he worked at the St. Bartholomew's Hospital in London. Later on he also received a Diploma in Psychological Medicine in 1931, and an M.A. 1930 and M.D. from Cambridge in 1935.

Ross Ashby started working in 1930 as a Clinical Psychiatrist in the London County Council. From 1936 until 1947 he was a Research Pathologist in the St Andrew's Hospital in Northampton in England. From 1945 to 1947 he served in India where he was a Major in the Royal Army Medical Corps.

When he returned to England he served as Director of Research of the Barnwood House Hospital in Gloucester from 1947 until 1959. For a year he was Director of the Burden Neurological Institute in Bristol. In 1960 he went to the United States and became Professor, Depts. of Biophysics and Electrical Engineering, University of Illinois at Urbana-Champaign, until his retirement in 1970.[2]

Ashby was president of the Society for General Systems Research from 1962 to 1964. He became a fellow of the Royal College of Psychiatry in 1971.

On March 4–6, 2004, a W. Ross Ashby centenary conference was held at the University of Illinois at Urbana-Champaign to mark the 100th anniversary of his birth. Presenters at the conference included Stuart Kauffman, Stephen Wolfram and George Klir.[3] . In February 2009 a special issue of the International Journal of General Systems was specifically devoted to Ashby and his work, containing papers from leading scholars such as Klaus Krippendorff, Stuart Umpleby and Kevin Warwick[4] .

Work

Despite being widely influential within cybernetics, systems theory and, more recently, complex systems, he is not as well known as many of the notable scientists his work influenced including Herbert Simon, Norbert Wiener, Ludwig von Bertalanffy, Stafford Beer and Stuart Kauffman.[5]

Journal

Ashby kept a journal for over 44 years in which he recorded his ideas about new theories. He started May 1928, when he was medical student at St. Bartholomew's Hospital in London. Over the years he wrote down a series of 25 volumes with intotal 7,400 pages. In 2003 these journals were donated to The British Library, London, and since 2008, they were made available online as The W. Ross Ashby Digital Archive.[6]

Cybernetics

Ross Ashby was one of the original members of the Ratio Club, a small informal dining club of young psychologists, physiologists, mathematicians and engineers who met to discuss issues in cybernetics. The club was founded in 1949 by the neurologist John Bates and continued to meet until 1958.

Earlier, in 1946, Alan Turing wrote a letter[7] to Ashby suggesting he use Turing's Automatic Computing Engine (ACE) for his experiments instead of building a special machine. In 1948 Ashby made the Homeostat.[8]

Variety

In *An Introduction to Cybernetics* Ashby formulated his Law of Requisite Variety [9] stating that "variety absorbs variety, defines the minimum number of states necessary for a controller to control a system of a given number of states." This law can be applied for example to the number of bits necessary in a digital computer to produce a required description or model.

In response Conant (1970) produced his so called "Good Regulator theorem" stating that "every Good Regulator of a System Must be a Model of that System" [10] .

Stafford Beer applied Variety to found management cybernetics and the Viable System Model. Working independently Gregory Chaitin followed this with algorithmic information theory.

See also

- Cybernetics
- Homeostat
- Intelligence amplification
- Self-organization
- Systems theory

Publications

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External links

- The W. Ross Ashby Digital Archive [15] includes an extensive biography, bibliography, letters, photographs, movies, and fully-indexed images of all 7,400 pages of Ashby's 25 volume journal.
- Homepage of William Ross Ashby [16] with a short text from the *Encyclopædia Britannica Yearbook* 1973, and some links.
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- The Law of Requisite Variety [21] in the Principia Cybernetica Web, 2001.
- 159 Aphorisms from Ashby and further links at the Cybernetics Society [22]
- W. Ross Ashby, Cybernetics and Requisite Variety [23] (1956) from *An Introduction to Cybernetics*
- W. Ross Ashby, Feedback, Adaptation and Stability [24] (1960) from *Design for a Brain*
- What is Cybernetics? [22] Livas short introductory videos on YouTube

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[15] http://www.rossashby.info/index.html
[16] http://www.gwu.edu/~asc/biographies/ashby/ashby.html
[17] http://cybersophe.org/writing/Asaro%20Ashby.pdf
[18] http://mitpress.mit.edu/catalog/item/default.asp?ttype=2&tid=11479
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[20] http://pcp.lanl.gov/ASHBBOOK.html
[21] http://pcp.lanl.gov/reqvar.html
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Ludwig von Bertalanffy

Ludwig von Bertalanffy	
Born	19 September 1901 Vienna, Austria
Died	12 June 1972 (aged 70) Buffalo, New York, USA
Fields	Biology and systems theory
Alma mater	University of Vienna
Known for	General System Theory
Influences	Rudolf Carnap, Gustav Theodor Fechner, Nicolai Hartmann, Otto Neurath, Moritz Schlick
Influenced	Russell L. Ackoff, Kenneth E. Boulding, Peter Checkland, C. West Churchman, Jay Wright Forrester, Ervin László, James Grier Miller, Anatol Rapoport

Karl Ludwig von Bertalanffy (September 19, 1901, Atzgersdorf near Vienna, Austria – June 12, 1972, Buffalo, New York, USA) was an Austrian-born biologist known as one of the founders of general systems theory. Von Bertalanffy grew up in Austria and subsequently worked in Vienna, London, Canada and the USA.

Biography

Ludwig von Bertalanffy was born and grew up in the little village of Atzgersdorf (now Liesing) near Vienna. Bertalanffy family had roots in 16th century nobility of Hungary, and included several scholars and court officials.[1] His grandfather Charles Joseph von Bertalanffy (1833-1912) had settled in Austria and had been a state theatre director in Klagenfurt, Graz, and Vienna, which were important positions in imperial Austria. His eldest son and Ludwig's father Gustav von Bertalanffy (1861-1919) had been prominent railway administrator. On his mother's side Ludwig's grandfather Joseph Vogel was imperial counsellor and a wealthy Vienna publisher. Ludwig's mother Charlotte Vogel was seventeen when she married the thirty-four year old Gustav. They divorced when Ludwig was ten, and both remarried outside the Catholic Church in civil ceremonies [2] .

Von Bertalanffy grew up as only child educated at home by private tutors until he was ten. When he went to the gymnasium/grammar school he was already well trained in self study, and kept studying on his own. In the famous neighbour biologist Paul Kammerer, he found himself an example.[3] In 1918 he started his studies with history of art and philosophy, firstly at the University of Innsbruck and then at the University of Vienna. He had to make a choice between studying philosophy of science and biology, and chose the latter because, according to him, one could always become a philosopher later, but not a biologist. In 1926 he finished his PhD thesis (translated title: Fechner and the problem of integration of higher order) about physicist and philosopher Gustav Theodor Fechner.[3]

Von Bertalanffy met his future wife Maria in April 1924 in the Austrian Alps. They met the first day and were almost never apart for the next forty-eight years.[4] She wanted to finish studying but never did, instead she would devote her life to Bertalanffy's career. Later in Canada would become his employee for some years and after his death she compiled two of Bertalanffy's last works. They had one child, who would go on to step into Bertalanffy's

footsteps in the field of cancer research.

Von Bertalanffy was a professor at the University of Vienna from 1934–48, University of London (1948–49), Université de Montréal (1949), University of Ottawa (1950–54), University of Southern California (1955–58), the Menninger Foundation (1958–60), University of Alberta (1961–68), and State University of New York at Buffalo (SUNY) (1969-72). In 1972, he died from a sudden heart attack.

Work

Bertalanffy according to Weckowicz (1989), "occupies an important position in the intellectual history of the twentieth century. His contributions went beyond biology, and extended to cybernetics, education, history, philosophy, psychiatry, psychology and sociology. Some of his admirers even believe that von Bertalanffy's general systems theory could provide a conceptual framework for all these disciplines".[1] He is seen as founder of the interdisciplinary school of thoughts known as general systems theory. Yet he spent his life in semi-obscurity, and he survives mostly in footnotes. Ludwig von Bertalanffy may well be the least known intellectual titan of the twentieth century.[5]

The individual growth model

The individual growth model published by von Bertalanffy in 1934 is widely used in biological models and exists in a number of permutations.

In its simplest version the so-called von Bertalanffy growth equation is expressed as a differential equation of length (*L*) over time (*t*):

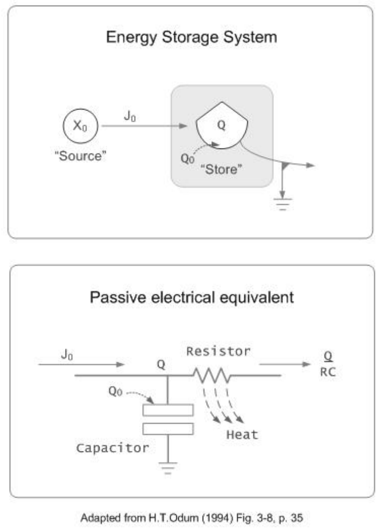
$$L'(t) = r_B \left(L_\infty - L(t)\right)$$

when r_B is the von Bertalanffy growth rate and L_∞ the ultimate length of the individual. This model was proposed earlier by **A. Pütter** in 1920 (*Arch. Gesamte Physiol. Mensch. Tiere*, **180**: 298-340).

The **Dynamic Energy Budget theory** provides a mechanistic explanation of this model in the case of isomorphs that experience a constant food availability. The inverse of the von Bertalanffy growth rate appears to depend linearly on the ultimate length, when different food levels are compared. The intercept relates to the maintenance costs, the slope to the rate at which reserve is mobilized for use by metabolism. The ultimate length equals the maximum length at high food availabilities.[6]

Bertalanffy Module

To honor Bertalanffy, ecological systems engineer and scientist Howard T. Odum named the storage symbol of his General Systems Language as the Bertalanffy module (see image right).[7]



Passive electrical schematic of the Bertalanffy module together with equivalent expression in the Energy Systems Language

General System Theory (GST)

The biologist is widely recognized for his contributions to science as a systems theorist; specifically, for the development of a theory known as General System Theory (GST). The theory attempted to provide alternatives to conventional models of organization. GST defined new foundations and developments as a generalized theory of systems with applications to numerous areas of study, emphasizing holism over reductionism, organism over mechanism.

Open systems

Bertalanffy's contribution to systems theory is best known for his theory of open systems. The system theorist argued that traditional closed system models based on classical science and the second law of thermodynamics were untenable. Bertalanffy maintained that “the conventional formulation of physics are, in principle, inapplicable to the living organism being open system having steady state. We may well suspect that many characteristics of living systems which are paradoxical in view of the laws of physics are a consequence of this fact.” [8] However, while closed physical systems were questioned, questions equally remained over whether or not open physical systems could justifiably lead to a definitive science for the application of an open systems view to a general theory of systems.

In Bertalanffy’s model, the theorist defined general principles of open systems and the limitations of conventional models. He ascribed applications to biology, information theory and cybernetics. Concerning biology, examples from the open systems view suggested they “may suffice to indicate briefly the large fields of application” that could be the “outlines of a wider generalization;” [9] from which, a hypothesis for cybernetics. Although potential applications exist in other areas, the theorist developed only the implications for biology and cybernetics. Bertalanffy also noted unsolved problems, which included continued questions over thermodynamics, thus the unsubstantiated claim that there are physical laws to support generalizations (particularly for information theory), and the need for further research into the problems and potential with the applications of the open system view from physics.

Systems in the social sciences

In the social sciences, Bertalanffy did believe that general systems concepts were applicable, e.g. theories that had been introduced into the field of sociology from a modern systems approach that included “the concept of general system, of feedback, information, communication, etc.” [10] The theorist critiqued classical “atomistic” conceptions of social systems and ideation “such as ‘social physics’ as was often attempted in a reductionist spirit.” [11] Bertalanffy also recognized difficulties with the application of a new general theory to social science due to the complexity of the intersections between natural sciences and human social systems. However, the theory still encouraged for new developments from sociology, to anthropology, economics, political science, and psychology among other areas. Today, Bertalanffy's GST remains a bridge for interdisciplinary study of systems in the social sciences.

See also

- Population dynamics
- Systems theory

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External links

- International Society for the Systems Sciences' [17] biography of Ludwig von Bertalanffy
- Bertalanffy Center for the Study of Systems Science [18] BCSSS in Vienna.

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Robert Rosen

Robert Rosen	
 Active web link to Professor Robert Rosen's large, colour photo [1]	
Born	27 June 1934 New York, USA
Died	28 December 1998 Rochester, New York, United States
Residence	US
Citizenship	American
Nationality	US
Ethnicity	American
Fields	Mathematical biology, Quantum Genetics, Biophysics
Institutions	State University of New York (SUNY) at Buffalo, and Professor of Biophysics at Dalhousie University
Alma mater	University of Chicago
Academic advisors	Professor Nicolas Rashevsky, the Founder of Mathematical Biology in USA
Notes Active web link to Dr. Robert Rosen's photo [1]	

See also arts and entertainment celebrity producer-writer-performer: Robert M. Rosen, Robert Ozn

Robert Rosen (27 June 1934, - 28 December 1998, Rochester, New York) was an American theoretical biologist and Professor of Biophysics at Dalhousie University[2] .

Biography

Robert Rosen was born on June 27, 1934 in Brownsville (a section of Brooklyn), in New York City. He studied biology, mathematics, physics, philosophy, and history—especially the history of science—and became a dedicated student of mathematics, physics, and biology. Then, under Professor Nicolas Rashevsky's guidance at the University of Chicago, he became a mathematical or theoretical biologist with a PhD in Mathematical Biology in 1959. His PhD research area was in Relational Biology, and he remained at the University of Chicago until 1964[3] . In 1964 Dr. Rosen was offered a full associate professorship with tenure at the University of Buffalo, now known as the State University of New York (SUNY) at Buffalo, holding a joint appointment at the Center for Theoretical Biology. In 1970, he took a sabbatical and spent a year as a Visiting Fellow at Robert Hutchins' Center for the Study of Democratic Institutions, in Santa Barbara, California. It was a seminal year for him, leading to the conception and development of what he later called Anticipatory Systems Theory, a corollary of his larger theoretical work on relational complexity, in which it is embedded. In 1975, he left SUNY at Buffalo and accepted a position at Dalhousie University, in Halifax, Nova Scotia, as a Killam Research Professor in the Department of Physiology and Biophysics, where he remained until he took early retirement in 1994.[4] He is survived by his wife, a daughter-Judith Rosen, and two sons.

He served as president of the Society for General Systems Research, (now known as ISSS), in 1980-81. See also the link to Dr. Robert Rosen's photo [1]

Research

Rosen's research was concerned with the most fundamental aspects of biology, specifically the question "What is life?" or "Why are living organisms alive?". Major themes in the work of Robert Rosen were:

- developing a specific definition of complexity that is based on relations and, by extension, principles of organization
- developing a rigorous theoretical foundation for living organisms as "anticipatory systems"

Rosen believed that the contemporary model of physics - which he thought to be based on an outdated Cartesian and Newtonian world of mechanisms - was inadequate to explain or describe the behavior of biological systems; that is, one could not properly answer the fundamental question "*What is life?*" from within a scientific foundation that is entirely reductionistic. He thought that approaching organisms with what he considered to be excessively reductionistic scientific methods and practices sacrifices the whole in order to study the parts, but what Rosen thought was that the whole could not be recaptured once the biological organization had been destroyed. His conclusion was that the very thing about living organisms biologists should be studying, the organization, was the first aspect of all biological systems to be thrown away in reductionist analysis. This is regarded as a limitation of the part of contemporary science which regards the machine or automaton as a model for all systems in the universe. Rosen came to regard the machine metaphor as the single biggest impediment to scientific exploration of questions in biology and concluded that the paradigm needs to be expanded beyond purely reductionist capabilities. In order to do this properly, he said there must be a sound theoretical foundation underlying the expansion and that relational complexity provided such a foundation. So it was that, rather than biology being a mere subset of the already known physics, it turned out that biology might have profound lessons for physics, and also science, in general.[5] .

Relational biology

Rosen's work proposes a methodology that he called *"Relational Biology"* which needs to be developed in addition to the current reductionistic approaches to science by molecular biologists. ("Relational" is a term he correctly attributes to Nicolas Rashevsky who published several papers on the importance of set-theoretical relations[6] in biology prior to Rosen's first reports on this subject). Rosen's relational approach to Biology is an extension and amplification of Nicolas Rashevsky's treatment of n-ary relations in, and among, organismic sets that he developed over two decades as a representation of both biological and social 'organisms'. Rosen's relational biology maintains that organisms, and indeed all systems, have a distinct quality called *"organization"* which is not part of the language of reductionism, as for example in molecular biology, although it is increasingly employed in systems biology. It has to do with more than purely structural or material aspects. For example, organization includes all relations between material parts, relations between the effects of interactions of the material parts, and relations with time and environment, to name a few. Many people sum up this aspect of complex systems[7] by saying that "*the whole is more than the sum of the parts"*. Relations between parts and between the effects of interactions must be considered as additional 'relational' parts, in some sense. Rosen said that organization must be independent from the material particles which seemingly constitute a living system. As he put it: "The human body completely changes the matter it is made of roughly every 8 weeks, through metabolism and repair. Yet, you're still you-- with all your memories, your personality... If science insists on chasing particles, they will follow them right through an organism and miss the organism entirely," (as told to his daughter, Ms. Judith Rosen[8]). Rosen's abstract relational biology approach focuses on a definition of living organisms, and all complex systems, in terms of their internal “organization" as open systems that cannot be reduced to their interacting components because of the multiple relations between metabolic and repair components that govern the organism's complex biodynamics. He deliberately chose the `simplest' graphs and categories for his representations of Metabolic-Replication Systems in small categories of sets endowed only

with the discrete topology of sets, envisaging this choice as the most general and less restrictive. It turns out however that the categories of **(M,R)**-systems are Cartesian closed, and may be considered in a very strict mathematical sense as subcategories of the category of sequential machines or automata, in a somewhat ironical vindication of the French philosopher Descartes' supposition that **all animals are only ellaborate machines** or *mechanisms*. The latter, mechanistic view prevails even today in most of general biology, but no longer in sociology and psychology where reductionist approaches have failed and fallen out of favour since the early 1970s.

Rosen's concept of complexity and complex scientific models

The clarification of the distinction between simple and complex scientific models became in later years a major goal of Rosen's published reports; Rosen maintained that modeling is at he very the essence of science and thought. His book *Anticipatory Systems* describes, in detail, what he termed the *modeling relation*. He showed the deep differences between a true modeling relation and a simulation (that is not based on such a modeling relation). In mathematical biology he is known as the originator of a class of relational models of living organisms, called "**(M,R)**-systems" that he devised, which he claimed that capture the minimal, or basic, capabilities that a material system would need in order to specify the simplest functional organisms, that are commonly said to be "alive". In this kind of system, **M** stands for the metabolic, and **R** stands for the 'repair', components or subsystems of a simple organism, (such as for example active 'repair' RNA molecules). Thus, his mode for determining life, or 'defining' life, in any given system is a functional one, not a material one, although he did consider in his 1970s published reports specific *dynamic realizations* of the simplest "**(M,R)**-systems" in terms of enzymes (**M**), RNA (**R**), and functional, duplicating DNA (his "**β**-mapping"). He went, however, even farther in this direction by claiming that when studying a complex system, one "can throw away the matter and study the organization order" to learn those things that are essential to defining in general an entire class of systems. This has been, however, taken too literally by a few of his former students who have not completely assimilated Robert Rosen's injunction of the need for a theory of *dynamic realizations* of such abstract components in specific molecular form in order to close the modeling loop for the simplest functional organisms (such as, for example, single-cell algae or microorganisms)[9] . He supported this claim (that he actually attributed to Nicolas Rashevsky) based on the fact that living organisms are a class of systems with an extremely wide range of material "ingredients", different structures, different habitats, different modes of living and reproduction, and yet we are somehow able to recognize them all as 'living', or functional organisms, without being however 'vitalists'. His approach, just like Rashevsky's latest theories of organismic sets[10] ,[11] , emphasizes biological organization over molecular structure in an attempt to bypass the *structure-functionality relationships* that are important to all experimental biologists, including physiologists. In contrast, a study of the specific material details of any given organism, or even of a whole species, will only tell us about how that type of organism "does it". Such a study doesn't approach what is common to all physiologically-functional organisms, i.e. "life". Relational approaches to theoretical biology would therefore allow us to study organisms in ways that preserve those essential qualities that we are trying to learn about, and that are common only to *functional* organisms. One needs conclude that Robert Rosen's approach belongs conceptually to what is now known as Functional Biology, as well as Complex Systems Biology, *albeit* in a highly abstract, mathematical form.

Quantum Biochemistry and Quantum Genetics

Rosen also questioned what he believed to be many aspects of mainstream interpretations of biochemistry and genetics. He objects to the idea that functional aspects in biological systems can be investigated via a material focus. One example: Rosen disputes that the functional capability of a biologically active protein can be investigated purely using the genetically encoded sequence of amino acids. This is because, he said, a protein must undergo a process of "folding" to attain its characteristic three-dimensional shape before it can become functionally active in the system. Yet, only the amino acid sequence is genetically coded. The mechanisms by which proteins fold are not completely known. He concluded, based on examples such as this, that phenotype cannot always be directly attributed to genotype and that the chemically active aspect of a biologically active protein relies on more than the sequence of

amino acids, from which it was constructed: there must be some other important factors at work, that he did not however attempt to specify or pin down.

Certain questions about Rosen's mathematical arguments were raised in a paper authored by Christopher Landauer and Kirstie L. Bellman which claimed that some of the mathematical formulations used by Rosen are problematic from a logical viewpoint. One notes however that such issues were also raised long time ago by Bertrand Russel and Alfred North Whitehead in their famous "*Principia Mathematica*" in relation to antinomies of set theory. As Rosen's mathematical formulation in his earlier papers was also based on set theory and the category of sets such issues have naturally re-surfaced. However, these issues have now been addressed by Robert Rosen in his recent book "*Life, Itself*", published posthumously in 2000. Furthermore, such basic problems of mathematical formulations of **(M,R)**--systems had already been resolved by other authors as early as 1973 by utilizing the Yoneda lemma in category theory, and the associated functorial construction in categories with (mathematical) structure[12] [13] . Such general category theory extensions of **(M,R)**-systems that avoid set theory paradoxes are based on William Lawvere's categorical approach and its extensions to higher-dimensional algebra. The mathematical and logical extension of *metabolic-replication systems* to generalized **(M,R)**-systems, or **G-MR**s, also involved a series of acknowledged letters exchanged between Robert Rosen and the latter authors during 1967—1980s, as well as letters exchanged with Nicolas Rashevsky up to 1972.

"*Life, Itself* and also his subsequent book "*Essays on Life Itself*", discuss also rather critically certain quantum genetics issues such as those introduced by Erwin Schrödinger in his famous early 1945 book "What Is Life?". (Note, by Judith Rosen, who owns the copyrights to her father's books: Some of the confusion is due to known errata introduced into the book, "Life, Itself," by the publisher. For example, the diagram that refers to "(M,R)-Systems" has more than one error; errors which do not exist in Rosen's manuscript for the book. These errata were made known to Columbia University Press when the company switched from hardcover to paperback version of the book (in 2006) but the errors were not corrected and remain in the paperback version as well. The book "Anticipatory Systems; Philosophical, Mathematical, and Methodological Foundations" has the same diagram, correctly represented.)

See also

- A Bibliography of Robert Rosen's publications. [14]
- system theory
  - Cybernetics and Systems Thinkers [15] overview by the Principia Cybernetica Web.
  - Society for General Systems Research
- Mathematical biology and Mathematical biophysics
  - Nicolas Rashevsky
  - Category theory
  - Category of sets
  - Society for Mathematical Biology
- complexity theory
  - Complex Systems Biology
- Quantum biology
  - Quantum Genetics
  - Quantum Biochemistry
- philosophy of science
  - What Is Life?
  - Ontology
  - Autopoiesis

Publications

Rosen has written several books and articles. A selection of his published books is as follows:

- 1970, *Dynamical Systems Theory in Biology* New York: Wiley Interscience.
- 1970, *Optimality Principles*, Rosen Enterprises
- 1978, *Fundamentals of Measurement and Representation of Natural Systems*, Elsevier Science Ltd,
- 1985, *Anticipatory Systems: Philosophical, Mathematical and Methodological Foundations*. Pergamon Press.
- 1991, *Life Itself: A Comprehensive Inquiry into the Nature, Origin, and Fabrication of Life*, Columbia University Press

Published posthumously:

- 2000, *Essays on Life Itself*, Columbia University Press.
- 2003, "Anticipatory Systems; Philosophical, Mathematical, and Methodolical Foundations", Rosen Enterprises
- 2003, *Rosennean Complexity*, Rosen Enterprises.
- 2003, *The Limits of the Limits Of Science*, Rosen Enterprises

Notes

[1] http://www.people.vcu.edu/~mikuleck/bobrosen.gif
[2] Autobiographical Reminiscences of Robert Rosen, *Axiomathes* (2006). Volume 16, Numbers 1-2/ March, 2006, DOI:10.1007/s10516-006-0001-6, pages 1-23 (http://www.springerlink.com/content/fk37800274466085/); Robert Rosen about his own educational background, his philosophy of science, and his general point of view.]
[3] "Autobiographical Reminiscences of Robert Rosen" (http://www.rosen-enterprises.com/RobertRosen/rrosenautobio.html)
[4] In Memory of Dr. Robert Rosen (http://communications.medicine.dal.ca/connection/feb1999/rosen.htm), Feb 1999, retrieved Oct 2007.
[5] Robert Rosen -- BiologyComplexity and Physics (http://www.panmere.com/rosen/rosensum.htm)
[6] Jon Awbrey "Relation theory" (the logical approach to relation theory) (http://planetphysics.org/encyclopedia/RelationTheory.html)
[7] http://www.springerlink.com/content/n8gw445012267381/I.C. Baianu, (Editor) "Robert Rosen's Work and Complex Systems Biology." *Axiomathes* (2006) Volume 16, Numbers 1-2 / March, 2006, DOI: 10.1007/s10516-005-4204-z , pages 25-34
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[13] I.C. Baianu and M. Marinescu: 1974, A Functorial Construction of **(M,R)**- Systems. *Revue Roumaine de Mathematiques Pures et Appliquees* **19**: 388-391
[14] http://users.viawest.net/~keirsey/rosenbiblio.html
[15] http://pespmc1.vub.ac.be/CSTHINK.html

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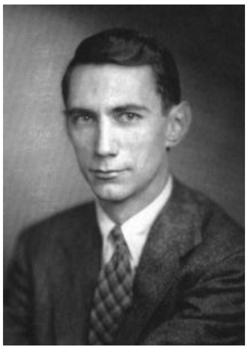
- Baianu, I.C.: 1970, "Organismic Supercategories: II. On Multistable Systems.", *Bulletin of Mathematical Biophysics*, **32**: 539-561.

External links

- "Autobiographical Reminiscences of Robert Rosen", *Axiomathes* (2006). Volume **16**, Numbers 1-2/ March, 2006, DOI:10.1007/s10516-006-0001-6, pages 1-23 (http://www.springerlink.com/content/fk37800274466085/); *Robert Rosen about his own educational background, his philosophy of science, and his general point of view.*]
- Autobiographical Reminiscences of Robert Rosen (http://www.rosen-enterprises.com/RobertRosen/rrosenautobio.html)
- "*Reminiscences of Nicolas Rashevsky*". (Late) 1972. by Robert Rosen.
- Robert Rosen's Biography (http://planetphysics.org/encyclopedia/RobertRosen.html)
- Jon Awbrey "Relation theory" (the logical approach to relation theory) (http://planetphysics.org/encyclopedia/RelationTheory.html)
- The Society for Mathematical Biology (http://www.smb.org/)
- "The Bulletin of Mathematical Biophysics" (http://www.springerlink.com/content/x513p402w52w1128/)
- Rosen: Complexity and Life (http://www.panmere.com/"Robert) A website exploring the work of Rosen.
- "Robert Rosen's Work and Complex Systems Biology." *Axiomathes* (2006) Volume 16, Numbers 1-2 / March, 2006 DOI: 10.1007/s10516-005-4204-z , pages 25-34. (http://www.springerlink.com/content/n8gw445012267381/)- A tribute to Robert Rosen by I.C. Baianu, (Editor of Axiomathes- Special Robert Rosen and Complexity Issue in 2006), Springer: Berlin and New York.
- Robert Rosen: June 27, 1934 — December 30, 1998 (http://www.people.vcu.edu/~mikuleck/Rosenreq.html) by Aloisius Louie.
- *Robert Rosen: The well posed question and its answer: why are organisms different from machines?* (http://www.people.vcu.edu/~mikuleck/PPRISS3.html) An essay by Donald C. Mikulecky.
- Panmere website on Rosennean Complexity (http://www.panmere.com/?page_id=10): "*Judith Rosen's website provides free biographical information, discussions of her father's work, and also free reprints of Robert Rosen's work*".
- Paper (http://content.aip.org/APCPCS/v627/i1/59_1.html) by Christopher Landauer and Kirstie L. Bellman criticising some of Rosen's mathematical formulations, followed by attempts to improve the formulations.

Claude Shannon

Claude Shannon	
 Claude Elwood Shannon (1916-2001)	
Born	April 30, 1916 Petoskey, Michigan, United States
Died	February 24, 2001 (aged 84) Medford, Massachusetts, United States
Residence	United States
Nationality	American
Fields	Electronic engineer and mathematician
Institutions	Bell Laboratories Massachusetts Institute of Technology Institute for Advanced Study
Alma mater	University of Michigan Massachusetts Institute of Technology
Doctoral advisor	Frank Lauren Hitchcock
Doctoral students	Danny Hillis Ivan Edward Sutherland William Robert Sutherland Heinrich Ernst
Known for	Information Theory Shannon–Fano coding Shannon–Hartley law Nyquist–Shannon sampling theorem Noisy channel coding theorem Shannon switching game Shannon number Shannon index Shannon's source coding theorem Shannon's expansion Shannon-Weaver model of communication Whittaker–Shannon interpolation formula
Notable awards	IEEE Medal of Honor Kyoto Prize

Claude Elwood Shannon (April 30, 1916 – February 24, 2001), an American electronic engineer and mathematician, is known as "the father of information theory".[1]

Shannon is famous for having founded information theory with one landmark paper published in 1948. But he is also credited with founding both digital computer and digital circuit design theory in 1937, when, as a 21-year-old master's student at MIT, he wrote a thesis demonstrating that electrical application of Boolean algebra could construct and resolve any logical, numerical relationship. It has been claimed that this was the most important master's thesis of all time.[2]

Biography

Shannon was born in Petoskey, Michigan. His father, Claude Sr (1862–1934), a descendant of early New Jersey settlers, was a businessman and for a while, Judge of Probate. His mother, Mabel Wolf Shannon (1890–1945), daughter of German immigrants, was a language teacher and for a number of years principal of Gaylord High School, Michigan. The first sixteen years of Shannon's life were spent in Gaylord, Michigan, where he attended public school, graduating from Gaylord High School in 1932. Shannon showed an inclination towards mechanical things. His best subjects were science and mathematics, and at home he constructed such devices as models of planes, a radio-controlled model boat and a telegraph system to a friend's house half a mile away. While growing up, he worked as a messenger for Western Union. His childhood hero was Thomas Edison, who he later learned was a distant cousin. Both were descendants of John Ogden, a colonial leader and an ancestor of many distinguished people.[3] [4]

Boolean theory

In 1932 he entered the University of Michigan, where he took a course that introduced him to the works of George Boole. He graduated in 1936 with two bachelor's degrees, one in electrical engineering and one in mathematics, then began graduate study at the Massachusetts Institute of Technology (MIT), where he worked on Vannevar Bush's differential analyzer, an analog computer.

While studying the complicated ad hoc circuits of the differential analyzer, Shannon saw that Boole's concepts could be used to great utility. A paper drawn from his 1937 master's thesis, *A Symbolic Analysis of Relay and Switching Circuits*[5] , was published in the 1938 issue of the *Transactions of the American Institute of Electrical Engineers*. It also earned Shannon the Alfred Noble American Institute of American Engineers Award in 1940. Howard Gardner, of Harvard University, called Shannon's thesis "possibly the most important, and also the most famous, master's thesis of the century."

Victor Shestakov, at Moscow State University, had proposed a theory of electric switches based on Boolean logic a little bit earlier than Shannon, in 1935, but the first publication of Shestakov's result took place in 1941, after the publication of Shannon's thesis.

In this work, Shannon proved that Boolean algebra and binary arithmetic could be used to simplify the arrangement of the electromechanical relays then used in telephone routing switches, then turned the concept upside down and also proved that it should be possible to use arrangements of relays to solve Boolean algebra problems. Exploiting this property of electrical switches to do logic is the basic concept that underlies all electronic digital computers. Shannon's work became the foundation of practical digital circuit design when it became widely known among the electrical engineering community during and after World War II. The theoretical rigor of Shannon's work completely replaced the *ad hoc* methods that had previously prevailed.

Flush with this success, Vannevar Bush suggested that Shannon work on his dissertation at Cold Spring Harbor Laboratory, funded by the Carnegie Institution headed by Bush, to develop similar mathematical relationships for Mendelian genetics, which resulted in Shannon's 1940 PhD thesis at MIT, *An Algebra for Theoretical Genetics*[6] .

In 1940, Shannon became a National Research Fellow at the Institute for Advanced Study in Princeton, New Jersey. At Princeton, Shannon had the opportunity to discuss his ideas with influential scientists and mathematicians such as Hermann Weyl and John von Neumann, and even had the occasional encounter with Albert Einstein. Shannon

worked freely across disciplines, and began to shape the ideas that would become information theory.[7]

Wartime research

Shannon then joined Bell Labs to work on fire-control systems and cryptography during World War II, under a contract with section D-2 (Control Systems section) of the National Defense Research Committee (NDRC).

For two months early in 1943, Shannon came into contact with the leading British cryptanalyst and mathematician Alan Turing. Turing had been posted to Washington to share with the US Navy's cryptanalytic service the methods used by the British Government Code and Cypher School at Bletchley Park to break the ciphers used by the German U-boats in the North Atlantic.[8] He was also interested in the encipherment of speech and to this end spent time at Bell Labs. Shannon and Turing met every day at teatime in the cafeteria.[8] Turing showed Shannon his seminal 1936 paper that defined what is now known as the "Universal Turing machine"[9] [10] which impressed him, as many of its ideas were complementary to his own.

In 1945, as the war was coming to an end, the NDRC was issuing a summary of technical reports as a last step prior to its eventual closing down. Inside the volume on fire control a special essay titled *Data Smoothing and Prediction in Fire-Control Systems*, coauthored by Shannon, Ralph Beebe Blackman, and Hendrik Wade Bode, formally treated the problem of smoothing the data in fire-control by analogy with "the problem of separating a signal from interfering noise in communications systems."[11] In other words it modeled the problem in terms of data and signal processing and thus heralded the coming of the information age.

His work on cryptography was even more closely related to his later publications on communication theory.[12] At the close of the war, he prepared a classified memorandum for Bell Telephone Labs entitled "A Mathematical Theory of Cryptography," dated September, 1945. A declassified version of this paper was subsequently published in 1949 as "Communication Theory of Secrecy Systems" in the *Bell System Technical Journal*. This paper incorporated many of the concepts and mathematical formulations that also appeared in his *A Mathematical Theory of Communication*. Shannon said that his wartime insights into communication theory and cryptography developed simultaneously and "they were so close together you couldn’t separate them".[13] In a footnote near the beginning of the classified report, Shannon announced his intention to "develop these results ... in a forthcoming memorandum on the transmission of information."[14]

Postwar contributions

In 1948 the promised memorandum appeared as "A Mathematical Theory of Communication", an article in two parts in the July and October issues of the *Bell System Technical Journal*. This work focuses on the problem of how best to encode the information a sender wants to transmit. In this fundamental work he used tools in probability theory, developed by Norbert Wiener, which were in their nascent stages of being applied to communication theory at that time. Shannon developed information entropy as a measure for the uncertainty in a message while essentially inventing the field of information theory.

The book, co-authored with Warren Weaver, *The Mathematical Theory of Communication*, reprints Shannon's 1948 article and Weaver's popularization of it, which is accessible to the non-specialist. Shannon's concepts were also popularized, subject to his own proofreading, in John Robinson Pierce's *Symbols, Signals, and Noise*.

Information theory's fundamental contribution to Natural language processing and Computational linguistics was further established in 1951, in his article "Prediction and Entropy of Printed English", proving that treating whitespace as the 27th letter of the alphabet actually lowers uncertainty in written language, providing a clear quantifiable link between cultural practice and probabilistic cognition.

Another notable paper published in 1949 is "Communication Theory of Secrecy Systems", a declassified version of his wartime work on the mathematical theory of cryptography, in which he proved that all theoretically unbreakable ciphers must have the same requirements as the one-time pad. He is also credited with the introduction of Sampling Theory, which is concerned with representing a continuous-time signal from a (uniform) discrete set of samples.

This theory was essential in enabling telecommunications to move from analog to digital transmissions systems in the 1960s and later.

He returned to MIT to hold an endowed chair in 1956.

Hobbies and inventions

Outside of his academic pursuits, Shannon was interested in juggling, unicycling, and chess. He also invented many devices, including rocket-powered flying discs, a motorized pogo stick, and a flame-throwing trumpet for a science exhibition. One of his more humorous devices was a box kept on his desk called the "Ultimate Machine", based on an idea by Marvin Minsky. Otherwise featureless, the box possessed a single switch on its side. When the switch was flipped, the lid of the box opened and a mechanical hand reached out, flipped off the switch, then retracted back inside the box. Renewed interest in the "Ultimate Machine" has emerged on YouTube and Thingiverse. In addition he built a device that could solve the Rubik's cube puzzle.[3]

He is also considered the co-inventor of the first wearable computer along with Edward O. Thorp.[15] The device was used to improve the odds when playing roulette.

Legacy and tributes

Shannon came to MIT in 1956 to join its faculty and to conduct work in the Research Laboratory of Electronics (RLE). He continued to serve on the MIT faculty until 1978. To commemorate his achievements, there were celebrations of his work in 2001, and there are currently five statues of Shannon: one at the University of Michigan; one at MIT in the Laboratory for Information and Decision Systems; one in Gaylord, Michigan; one at the University of California, San Diego; and another at Bell Labs. After the breakup of the Bell system, the part of Bell Labs that remained with AT&T was named Shannon Labs in his honor.

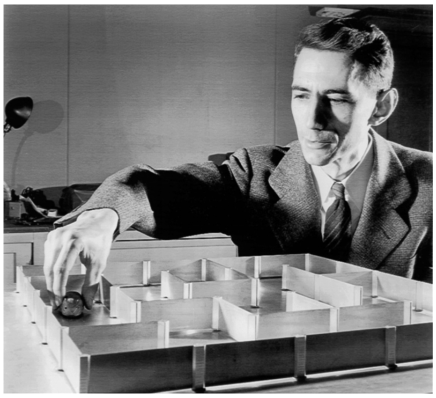
Robert Gallager has called Shannon the greatest scientist of the 20th century. According to Neil Sloane, an AT&T Fellow who co-edited Shannon's large collection of papers in 1993, the perspective introduced by Shannon's communication theory (now called information theory) is the foundation of the digital revolution, and every device containing a microprocessor or microcontroller is a conceptual descendant of Shannon's 1948 publication:[16] "He's one of the great men of the century. Without him, none of the things we know today would exist. The whole digital revolution started with him."[17]

Shannon developed Alzheimer's disease, and spent his last few years in a Massachusetts nursing home. He was survived by his wife, Mary Elizabeth Moore Shannon; a son, Andrew Moore Shannon; a daughter, Margarita Shannon; a sister, Catherine S. Kay; and two granddaughters.[18] [19]

Shannon was oblivious to the marvels of the digital revolution because his mind was ravaged by Alzheimer's disease. His wife mentioned in his obituary that had it not been for Alzheimer's "he would have been bemused" by it all.[17]

Other work

Shannon's mouse



Shannon and his famous electromechanical mouse *Theseus* (named after Theseus from Greek mythology) which he tried to have solve the maze in one of the first experiments in artificial intelligence

Theseus, created in 1950, was a magnetic mouse controlled by a relay circuit that enabled it to move around a maze of 25 squares. Its dimensions were the same as an average mouse.[1] The maze configuration was flexible and it could be modified at will.[1] The mouse was designed to search through the corridors until it found the target. Having travelled through the maze, the mouse would then be placed anywhere it had been before and because of its prior experience it could go directly to the target. If placed in unfamiliar territory, it was programmed to search until it reached a known location and then it would proceed to the target, adding the new knowledge to its memory thus learning.[1] Shannon's mouse appears to have been the first learning device of its kind.[1]

Shannon's computer chess program

In 1950 Shannon published a groundbreaking paper on computer chess entitled *Programming a Computer for Playing Chess*. It describes how a machine or computer could be made to play a reasonable game of chess. His process for having the computer decide on which move to make is a minimax procedure, based on an evaluation function of a given chess position. Shannon gave a rough example of an evaluation function in which the value of the black position was subtracted from that of the white position. *Material* was counted according to the usual relative chess piece relative value (1 point for a pawn, 3 points for a knight or bishop, 5 points for a rook, and 9 points for a queen). He considered some positional factors, subtracting ½ point for each doubled pawns, backward pawn, and isolated pawn. Another positional factor in the evaluation function was *mobility*, adding 0.1 point for each legal move available. Finally, he considered checkmate to be the capture of the king, and gave the king the artificial value of 200 points. Quoting from the paper:

> *The coefficients .5 and .1 are merely the writer's rough estimate. Furthermore, there are many other terms that should be included. The formula is given only for illustrative purposes. Checkmate has been artificially included here by giving the king the large value 200 (anything greater than the maximum of all other terms would do).*

The evaluation function is clearly for illustrative purposes, as Shannon stated. For example, according to the function, pawns that are doubled as well as isolated would have no value at all, which is clearly unrealistic.

The Las Vegas connection: Information theory and its applications to game theory

Shannon and his wife Betty also used to go on weekends to Las Vegas with M.I.T. mathematician Ed Thorp,[20] and made very successful forays in blackjack using game theory type methods co-developed with fellow Bell Labs associate, physicist John L. Kelly Jr. based on principles of information theory.[21] They made a fortune, as detailed in the book *Fortune's Formula* by William Poundstone and corroborated by the writings of Elwyn Berlekamp,[22] Kelly's research assistant in 1960 and 1962.[2] Shannon and Thorp also applied the same theory, later known as the *Kelly criterion*, to the stock market with even better results.[23]

Shannon's maxim

Shannon formulated a version of Kerckhoffs' principle as "the enemy knows the system". In this form it is known as "Shannon's maxim".

Biographical notes

He met his wife Betty when she was a numerical analyst at Bell Labs.

Awards and honors list

- Alfred Noble Prize, 1939
- Morris Liebmann Memorial Award of the Institute of Radio Engineers, 1949
- Yale University (Master of Science), 1954
- Stuart Ballantine Medal of the Franklin Institute, 1955
- Research Corporation Award, 1956
- University of Michigan, honorary doctorate, 1961
- Rice University Medal of Honor, 1962
- Princeton University, honorary doctorate, 1962
- Marvin J. Kelly Award, 1962
- University of Edinburgh, honorary doctorate, 1964
- University of Pittsburgh, honorary doctorate, 1964
- Institute of Electrical and Electronics Engineers Medal of Honor, 1966
- National Medal of Science, 1966, presented by President Lyndon B. Johnson
- Golden Plate Award, 1967
- Northwestern University, honorary doctorate, 1970
- Harvey Prize, the Technion of Haifa, Israel, 1972
- Royal Netherlands Academy of Arts and Sciences (KNAW), foreign member, 1975
- University of Oxford, honorary doctorate, 1978
- Joseph Jacquard Award, 1978
- Harold Pender Award, 1978
- University of East Anglia, honorary doctorate, 1982
- Carnegie Mellon University, honorary doctorate, 1984
- Audio Engineering Society Gold Medal, 1985
- Kyoto Prize, 1985
- Tufts University, honorary doctorate, 1987
- University of Pennsylvania, honorary doctorate, 1991
- Eduard Rhein Prize, 1991
- National Inventors Hall of Fame inducted, 2004

See also

- Shannon–Fano coding
- Shannon–Hartley theorem
- Nyquist–Shannon sampling theorem
- Noisy channel coding theorem
- Rate distortion theory
- Information theory
- Channel Capacity
- Confusion and diffusion
- One-time pad
- Shannon switching game
- Shannon number
- Claude E. Shannon Award
- Shannon index
- Shannon's source coding theorem
- Information entropy
- Shannon's expansion

Further reading

- Claude E. Shannon: *A Mathematical Theory of Communication*, Bell System Technical Journal, Vol. 27, pp. 379–423, 623–656, 1948.
- Claude E. Shannon and Warren Weaver: *The Mathematical Theory of Communication.* The University of Illinois Press, Urbana, Illinois, 1949. ISBN 0-252-72548-4
- Rethnakaran Pulikkoonattu - Eric W. Weisstein: Mathworld biography of Shannon, Claude Elwood (1916-2001) [24]
- Claude E. Shannon: *Programming a Computer for Playing Chess*, Philosophical Magazine, Ser.7, Vol. 41, No. 314, March 1950. (Available online under *External links* below)
- David Levy: *Computer Gamesmanship: Elements of Intelligent Game Design*, Simon & Schuster, 1983. ISBN 0-671-49532-1

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- David Mindell, Jérôme Segal, Slava Gerovitch, "From Communications Engineering to Communications Science: Cybernetics and Information Theory in the United States, France, and the Soviet Union" in Walker, Mark (Ed.), *Science and Ideology: A Comparative History*, Routledge, London, 2003, pp. 66-95.
- Poundstone, William, *Fortune's Formula*, Hill & Wang, 2005, ISNB-13 978-0-8090-4599-0

Shannon videos

- Shannon's video machines [25]
- Shannon - father of the information age [26]

External links

- C. E. Shannon, *An algebra for theoretical genetics,* Massachusetts Institute of Technology, Ph.D. Thesis, MIT-THESES//1940–3 (1940) Online text at MIT [27]
- Shannon's math genealogy [28]
- Shannon's NNDB profile [29]
- *A Mathematical Theory of Communication* [30]
- *Communication Theory of Secrecy Systems* [31]
- *Communication in the Presence of Noise* [32]
- Summary of Shannon's life and career [33]
- Biographical summary from Shannon's collected papers [34]
- Video documentary: "Claude Shannon - Father of the Information Age" [35]
- Mathematical Theory of Claude Shannon [36] In-depth MIT class paper on the development of Shannon's work to 1948.
- Retrospective at the University of Michigan [37]
- Shannon's University of Michigan profile [38]
- Notes on Computer-Generated Text [39]
- Shannon's Juggling Theorem and Juggling Robots [40]
- Color Photo of Shannon, Juggling [41]
- Shannon's paper on computer chess, text [42]
- Shannon's paper on computer chess [43]PDF (175 KiB)
- Shannon's paper on computer chess, text, alternate source [44]
- A Bibliography of His Collected Papers [45]
- A Register of His Papers in the Library of Congress [46]
- The Technium: The (Unspeakable) Ultimate Machine [47]
- The Most Beautiful Machine. [48] (aka the "Ultimate Machine") It's a communication based on the functions ON and OFF.
- Guizzo, "The Essential Message: Claude Shannon and the Making of Information Theory" [49]
- Article on Claude Shannon in a magazine by Shivaprasad Khened [50]

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[2] Poundstone, William: *Fortune's Formula : The Untold Story of the Scientific Betting System That Beat the Casinos and Wall Street* (http://www.amazon.com/gp/reader/0809046377)

[3] MIT Professor Claude Shannon dies; was founder of digital communications (http://web.mit.edu/newsoffice/2001/shannon.html), MIT - News office, Cambridge, Massachusetts, February 27, 2001

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[21] John Kelly by William Poundstone website (http://home.williampoundstone.net/Kelly.htm)

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[25] http://www.youtube.com/watch?v=sBHGzRxfeJY

[26] http://www.youtube.com/watch?v=z2Whj_nL-x8

[27] http://hdl.handle.net/1721.1/11174

[28] http://www.genealogy.math.ndsu.nodak.edu/id.php?id=42920

[29] http://www.nndb.com/people/934/000023865/

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Richard E. Bellman

Richard E. Bellman	
Born	August 26, 1920 New York City, New York
Died	March 19, 1984 (aged 63)
Fields	Mathematics and Control theory
Alma mater	Princeton University University of Wisconsin–Madison Brooklyn College
Known for	Dynamic programming

Richard Ernest Bellman (August 26, 1920 – March 19, 1984) was an applied mathematician, celebrated for his invention of dynamic programming in 1953, and important contributions in other fields of mathematics.

Biography

Bellman was born in 1920 in New York City, where his father John James Bellman ran a small grocery store on Bergen Street near Prospect Park in Brooklyn. Bellman completed his studies at Abraham Lincoln High School in 1937[1] , and studied mathematics at Brooklyn College where he received a BA in 1941. He later earned an MA from the University of Wisconsin–Madison. During World War II he worked for a Theoretical Physics Division group in Los Alamos. In 1946 he received his Ph.D. at Princeton under the supervision of Solomon Lefschetz.[2]

He was a professor at the University of Southern California, a Fellow in the American Academy of Arts and Sciences (1975), and a member of the National Academy of Engineering (1977).

He was awarded the IEEE Medal of Honor in 1979, "for contributions to decision processes and control system theory, particularly the creation and application of dynamic programming". His key work is the Bellman equation.

Work

Bellman equation

A Bellman equation, also known as a *dynamic programming equation*, is a necessary condition for optimality associated with the mathematical optimization method known as dynamic programming. Almost any problem which can be solved using optimal control theory can also be solved by analyzing the appropriate Bellman equation. The Bellman equation was first applied to engineering control theory and to other topics in applied mathematics, and subsequently became an important tool in economic theory.

Hamilton-Jacobi-Bellman

The Hamilton-Jacobi-Bellman equation (HJB) equation is a partial differential equation which is central to optimal control theory. The solution of the HJB equation is the 'value function', which gives the optimal cost-to-go for a given dynamical system with an associated cost function. Classical variational problems, for example, the brachistochrone problem can be solved using this method as well.

The equation is a result of the theory of dynamic programming which was pioneered in the 1950s by Richard Bellman and coworkers. The corresponding discrete-time equation is usually referred to as the Bellman equation. In continuous time, the result can be seen as an extension of earlier work in classical physics on the Hamilton-Jacobi equation by William Rowan Hamilton and Carl Gustav Jacob Jacobi.

Curse of dimensionality

The "Curse of dimensionality", is a term coined by Bellman to describe the problem caused by the exponential increase in volume associated with adding extra dimensions to a (mathematical) space. One implication of the curse of dimensionality is that some methods for numerical solution of the Bellman equation require vastly more computer time when there are more state variables in the value function.

For example, 100 evenly-spaced sample points suffice to sample a unit interval with no more than 0.01 distance between points; an equivalent sampling of a 10-dimensional unit hypercube with a lattice with a spacing of 0.01 between adjacent points would require 10^{20} sample points: thus, in some sense, the 10-dimensional hypercube can be said to be a factor of 10^{18} "larger" than the unit interval. (Adapted from an example by R. E. Bellman, see below.)

Bellman–Ford algorithm

The Bellman-Ford algorithm sometimes referred to as the Label Correcting Algorithm, computes single-source shortest paths in a weighted digraph (where some of the edge weights may be negative). Dijkstra's algorithm accomplishes the same problem with a lower running time, but requires edge weights to be non-negative. Thus, Bellman–Ford is usually used only when there are negative edge weights.

Publications

Over the course of his career he published 619 papers and 39 books. During the last 11 years of his life he published over 100 papers despite suffering from crippling complications of a brain surgery (Dreyfus, 2003). A selection[1] :

- 1959. *Asymptotic Behavior of Solutions of Differential Equations*
- 1961. *An Introduction to Inequalities*
- 1961. *Adaptive Control Processes: A Guided Tour*
- 1962. *Applied Dynamic Programming*
- 1967. *Introduction to the Mathematical Theory of Control Processes*
- 1970. *Algorithms, Graphs and Computers*
- 1972. *Dynamic Programming and Partial Differential Equations*
- 1982. *Mathematical Aspects of Scheduling and Applications*
- 1983. *Mathematical Methods in Medicine*
- 1984. *Partial Differential Equations*
- 1984. *Eye of the Hurricane: An Autobiography,* World Scientific Publishing.
- 1985. *Artificial Intelligence*
- 1995. *Modern Elementary Differential Equations*
- 1997. *Introduction to Matrix Analysis*
- 2003. *Dynamic Programming*
- 2003. *Perturbation Techniques in Mathematics, Engineering and Physics*

- 2003. *Stability Theory of Differential Equations*

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- Stuart Dreyfus (2003) "Richard Ernest Bellman" [5]. In: *International Transactions in Operational Research*. Vol 10, no. 5, Pages 543 - 545
- Salvador Sanabria. Richard Bellman's Biography [6]. Paper at www-math.cudenver.edu

External links

- IEEE History Center - Legacies [7]
- Harold J. Kushner's speech when accepting the Richard E. Bellman Control Heritage Award [8]
- IEEE biography [9]

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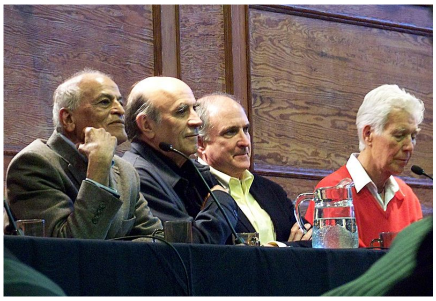
Brian Goodwin

Brian Carey Goodwin (1931 – 15 July 2009) was a Canadian mathematician and biologist.

He was Professor Emeritus at the Open University.



Brian Goodwin (on the right).

Biography

Brian Goodwin was born in Montreal, Canada in 1931. He studied biology at McGill University and then emigrated to the UK, under a Rhodes Scholarship for studying mathematics at Oxford. He got his PhD. at the University of Edinburgh. His first teaching job, in mathematics, was at Oxford University and then moved to Sussex University until 1983 when he became a full professor at the Open University in Milton Keynes until retirement in 1992. Thereafter, he taught at the Schumacher College in Devon, UK. Goodwin has also a research position at the MIT and was a long time visitor of several institutions including the UNAM in Mexico City. He was a founding member of the Santa Fe Institute in New Mexico where he also served as an external faculty for several years [1]

Brian Goodwin died in hospital in 2009, after surgery resulting from a fall from his bike.[2]

Publications

Books

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- A New Science of Qualities: a Talk With Brian Goodwin [3]
- An interview with Professor Brian Goodwin [4]

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[3] http://www.edge.org/3rd_culture/goodwin/goodwin_p1.html
[4] http://ngin.tripod.com/article8.htm

John von Neumann

John von Neumann

John von Neumann in the 1940s

Born	December 28, 1903 Budapest, Austria-Hungary
Died	February 8, 1957 (aged 53) Washington, D.C., United States
Residence	United States
Nationality	Hungarian and American
Ethnicity	Jewish–Hungarian
Fields	Mathematics and computer science
Institutions	University of Berlin Princeton University Institute for Advanced Study Site Y, Los Alamos
Alma mater	University of Pázmány Péter ETH Zürich
Doctoral advisor	Leopold Fejér
Doctoral students	Donald B. Gillies Israel Halperin John P. Mayberry
Other notable students	Paul Halmos Clifford Hugh Dowker

Known for	von Neumann Equation Game theory von Neumann algebras von Neumann architecture Von Neumann bicommutant theorem Von Neumann cellular automaton Von Neumann universal constructor Von Neumann entropy Von Neumann regular ring Von Neumann–Bernays–Gödel set theory Von Neumann universe Von Neumann conjecture Von Neumann's inequality Stone–von Neumann theorem Von Neumann stability analysis Minimax theorem Von Neumann extractor Von Neumann ergodic theorem Direct integral
Notable awards	Enrico Fermi Award (1956)
Signature 	

John von Neumann (December 28, 1903 – February 8, 1957) was a Hungarian American mathematician who made major contributions to a vast range of fields,[1] including set theory, functional analysis, quantum mechanics, ergodic theory, continuous geometry, economics and game theory, computer science, numerical analysis, hydrodynamics (of explosions), and statistics, as well as many other mathematical fields. He is generally regarded as one of the greatest mathematicians in modern history.[2] The mathematician Jean Dieudonné called von Neumann "the last of the great mathematicians",[3] while Peter Lax described him as possessing the most "fearsome technical prowess" and "scintillating intellect" of the century.[4] Even in Budapest, in the time that produced geniuses like von Kármán (b. 1881), Szilárd (b. 1898), Wigner (b. 1902), and Teller (b. 1908), his brilliance stood out.[5]

Von Neumann was a pioneer of the application of operator theory to quantum mechanics, in the development of functional analysis, a principal member of the Manhattan Project and the Institute for Advanced Study in Princeton (as one of the few originally appointed), and a key figure in the development of game theory[1] [6] and the concepts of cellular automata[1] and the universal constructor. Along with Edward Teller and Stanislaw Ulam, von Neumann worked out key steps in the nuclear physics involved in thermonuclear reactions and the hydrogen bomb.

Biography

The eldest of three brothers, von Neumann was born **Neumann János Lajos** (in Hungarian the family name comes first) on December 28, 1903 in Budapest, Austro-Hungarian Empire, to a wealthy Jewish family.[7] His father was Neumann Miksa (Max Neumann), a lawyer who worked in a bank. His mother was Kann Margit (Margaret Kann). Von Neumann's ancestors had originally immigrated to Hungary from Russia.

János, nicknamed "Jancsi" (Johnny), was a child prodigy who showed an aptitude for languages, memorization, and mathematics. By the age of six, he could exchange jokes in Classical Greek, memorise telephone directories, and displayed prodigious mental calculation abilities.[8] He entered the German-speaking Lutheran Fasori Gimnázium in Budapest in 1911. Although he attended school at the grade level appropriate to his age, his father hired private tutors to give him advanced instruction in those areas in which he had displayed an aptitude. Recognised as a mathematical prodigy, at the age of 15 he began to study under Gábor Szegő. On their first meeting, Szegő was so impressed with the boy's mathematical talent that he was brought to tears.[9] In 1913, his father was rewarded with

ennoblement for his service to the Austro-Hungarian empire. (After becoming semi-autonomous in 1867, Hungary had found itself in need of a vibrant mercantile class.) The Neumann family thus acquiring the title *margittai*, Neumann János became margittai Neumann János (John Neumann of Margitta), which he later changed to the German Johann von Neumann. He received his Ph.D. in mathematics (with minors in experimental physics and chemistry) from Pázmány Péter University in Budapest at the age of 22.[1] He simultaneously earned his diploma in chemical engineering from the ETH Zurich in Switzerland[1] at the behest of his father, who wanted his son to invest his time in a more financially viable endeavour than mathematics. Between 1926 and 1930, he taught as a Privatdozent at the University of Berlin, the youngest in its history. By age 25, he had published ten major papers, and by 30, nearly 36.

Max von Neumann died in 1929. In 1930, von Neumann, his mother, and his brothers emigrated to the United States. He anglicized his first name to John, keeping the Austrian-aristocratic surname of von Neumann, whereas his brothers adopted surnames Vonneumann and Neumann (using the *de Neumann* form briefly when first in the U.S.).

Von Neumann was invited to Princeton University, New Jersey in 1930, and, subsequently, was one of the first four people selected for the faculty of the Institute for Advanced Study (two of the others being Albert Einstein and Kurt Gödel), where he remained a mathematics professor from its formation in 1933 until his death.

In 1937, von Neumann became a naturalized citizen of the US. In 1938, von Neumann was awarded the Bôcher Memorial Prize for his work in analysis.

Von Neumann married twice. He married Mariette Kövesi in 1930, just prior to emigrating to the United States. They had one daughter (von Neumann's only child), Marina, who is now a distinguished professor of international trade and public policy at the University of Michigan. The couple divorced in 1937. In 1938, von Neumann married Klari Dan, whom he had met during his last trips back to Budapest prior to the outbreak of World War II. The von Neumanns were very active socially within the Princeton academic community, and it is from this aspect of his life that many of the anecdotes which surround von Neumann's legend originate.

Gravestone of John von Neumann

In 1955, von Neumann was diagnosed with what was either bone or pancreatic cancer.[10] While he was in the hospital he wrote a short monograph, The Computer and the Brain, observing that the basic computing hardware of the brain indicated a different methodology than the one used in developing the computer. Von Neumann died a year and a half later, in great pain. While at Walter Reed Hospital in Washington, D.C., he invited a Roman Catholic priest, Father Anselm Strittmatter, O.S.B., to visit him for consultation (a move which shocked some of von Neumann's friends).[11] The priest then administered to him the last Sacraments.[12] He died under military security lest he reveal military secrets while heavily medicated. John von Neumann was buried at Princeton Cemetery in Princeton, Mercer County, New Jersey.[13]

Von Neumann wrote 150 published papers in his life; 60 in pure mathematics, 20 in physics, and 60 in applied mathematics. His last work, published in book form as *The Computer and the Brain*, gives an indication of the direction of his interests at the time of his death.

Logic and set theory

The axiomatization of mathematics, on the model of Euclid's Elements, had reached new levels of rigor and breadth at the end of the 19th century, particularly in arithmetic (thanks to Richard Dedekind and Giuseppe Peano) and geometry (thanks to David Hilbert). At the beginning of the twentieth century, set theory, the new branch of mathematics discovered by Georg Cantor, and thrown into crisis by Bertrand Russell with the discovery of his famous paradox (on the set of all sets which do not belong to themselves), had not yet been formalized.

The problem of an adequate axiomatization of set theory was resolved implicitly about twenty years later (by Ernst Zermelo and Abraham Fraenkel) by way of a series of principles which allowed for the construction of all sets used in the actual practice of mathematics, but which did not explicitly exclude the possibility of the existence of sets which belong to themselves. In his doctoral thesis of 1925, von Neumann demonstrated how it was possible to exclude this possibility in two complementary ways: the *axiom of foundation* and the notion of *class.*

The axiom of foundation established that every set can be constructed from the bottom up in an ordered succession of steps by way of the principles of Zermelo and Fraenkel, in such a manner that if one set belongs to another then the first must necessarily come before the second in the succession (hence excluding the possibility of a set belonging to itself.) In order to demonstrate that the addition of this new axiom to the others did not produce contradictions, von Neumann introduced a method of demonstration (called the *method of inner models*) which later became an essential instrument in set theory.

The second approach to the problem took as its base the notion of class, and defines a set as a class which belongs to other classes, while a *proper class* is defined as a class which does not belong to other classes. Under the Zermelo/Fraenkel approach, the axioms impede the construction of a set of all sets which do not belong to themselves. In contrast, under the von Neumann approach, the class of all sets which do not belong to themselves can be constructed, but it is a *proper class* and not a set.

With this contribution of von Neumann, the axiomatic system of the theory of sets became fully satisfactory, and the next question was whether or not it was also definitive, and not subject to improvement. A strongly negative answer arrived in September 1930 at the historic mathematical Congress of Königsberg, in which Kurt Gödel announced his first theorem of incompleteness: the usual axiomatic systems are incomplete, in the sense that they cannot prove every truth which is expressible in their language. This result was sufficiently innovative as to confound the majority of mathematicians of the time. But von Neumann, who had participated at the Congress, confirmed his fame as an instantaneous thinker, and in less than a month was able to communicate to Gödel himself an interesting consequence of his theorem: namely that the usual axiomatic systems are unable to demonstrate their own consistency. It is precisely this consequence which has attracted the most attention, even if Gödel originally considered it only a curiosity, and had derived it independently anyway (it is for this reason that the result is called *Gödel's second theorem*, without mention of von Neumann.)

Quantum mechanics

At the International Congress of Mathematicians of 1900, David Hilbert presented his famous list of twenty-three problems considered central for the development of the mathematics of the new century. The sixth of these was *the axiomatization of physical theories.* Among the new physical theories of the century the only one which had yet to receive such a treatment by the end of the 1930s was quantum mechanics. Quantum mechanics found itself in a condition of foundational crisis similar to that of set theory at the beginning of the century, facing problems of both philosophical and technical natures. On the one hand, its apparent non-determinism had not been reduced to an explanation of a deterministic form. On the other, there still existed two independent but equivalent heuristic formulations, the so-called matrix mechanical formulation due to Werner Heisenberg and the wave mechanical formulation due to Erwin Schrödinger, but there was not yet a single, unified satisfactory theoretical formulation.

After having completed the axiomatization of set theory, von Neumann began to confront the axiomatization of quantum mechanics. He immediately realized, in 1926, that a quantum system could be considered as a point in a so-called Hilbert space, analogous to the 6N dimension (N is the number of particles, 3 general coordinate and 3 canonical momentum for each) phase space of classical mechanics but with infinitely many dimensions (corresponding to the infinitely many possible states of the system) instead: the traditional physical quantities (e.g., position and momentum) could therefore be represented as particular linear operators operating in these spaces. The *physics* of quantum mechanics was thereby reduced to the *mathematics* of the linear Hermitian operators on Hilbert spaces.

For example, the famous uncertainty principle of Heisenberg, according to which the determination of the position of a particle prevents the determination of its momentum and vice versa, is translated into the *non-commutativity* of the two corresponding operators. This new mathematical formulation included as special cases the formulations of both Heisenberg and Schrödinger, and culminated in the 1932 classic *The Mathematical Foundations of Quantum Mechanics.* However, physicists generally ended up preferring another approach to that of von Neumann (which was considered elegant and satisfactory by mathematicians). This approach was formulated in 1930 by Paul Dirac.

Von Neumann's abstract treatment permitted him also to confront the foundational issue of determinism vs. non-determinism and in the book he demonstrated a theorem according to which quantum mechanics could not possibly be derived by statistical approximation from a deterministic theory of the type used in classical mechanics. This demonstration contained a conceptual error, but it helped to inaugurate a line of research which, through the work of John Stuart Bell in 1964 on Bell's Theorem and the experiments of Alain Aspect in 1982, demonstrated that quantum physics requires a *notion of reality* substantially different from that of classical physics.

Economics and game theory

Von Neumann's first significant contribution to economics was the minimax theorem of 1928. This theorem establishes that in certain zero sum games with perfect information (i.e., in which players know at each time all moves that have taken place so far), there exists a strategy for each player which allows both players to minimize their maximum losses (hence the name minimax). When examining every possible strategy, a player must consider all the possible responses of the player's adversary and the maximum loss. The player then plays out the strategy which will result in the minimization of this maximum loss. Such a strategy, which minimizes the maximum loss, is called optimal for both players just in case their minimaxes are equal (in absolute value) and contrary (in sign). If the common value is zero, the game becomes pointless.

Von Neumann eventually improved and extended the minimax theorem to include games involving imperfect information and games with more than two players. This work culminated in the 1944 classic *Theory of Games and Economic Behavior* (written with Oskar Morgenstern). The public interest in this work was such that The New York Times ran a front page story, something which only Einstein had previously elicited.

Von Neumann's second important contribution in this area was the solution, in 1937, of a problem first described by Léon Walras in 1874, the existence of situations of equilibrium in mathematical models of market development based on supply and demand. He first recognized that such a model should be expressed through disequations and not equations, and then he found a solution to Walras' problem by applying a fixed-point theorem derived from the work of L. E. J. Brouwer. The lasting importance of the work on general equilibria and the methodology of fixed point theorems is underscored by the awarding of Nobel prizes in 1972 to Kenneth Arrow, in 1983 to Gérard Debreu, and in 1994 to John Nash who had improved von Neumann's theory in his Princeton Ph.D thesis.

Von Neumann was also the inventor of the method of proof, used in game theory, known as backward induction (which he first published in 1944 in the book co-authored with Morgenstern, *Theory of Games and Economic Behaviour*).[14]

Nuclear weapons

John von Neumann's wartime Los Alamos ID badge photo.

Beginning in the late 1930s, von Neumann began to take more of an interest in applied (as opposed to pure) mathematics. In particular, he developed an expertise in explosions—phenomena which are difficult to model mathematically. This led him to a large number of military consultancies, primarily for the Navy, which in turn led to his involvement in the Manhattan Project. The involvement included frequent trips by train to the project's secret research facilities in Los Alamos, New Mexico.[1]

Von Neumann's principal contribution to the atomic bomb itself was in the concept and design of the explosive lenses needed to compress the plutonium core of the Trinity test device and the "Fat Man" weapon that was later dropped on Nagasaki. While von Neumann did not originate the "implosion" concept, he was one of its most persistent proponents, encouraging its continued development against the instincts of many of his colleagues, who felt such a design to be unworkable. The lens shape design work was completed by July 1944.

In a visit to Los Alamos in September 1944, von Neumann showed that the pressure increase from explosion shock wave reflection from solid objects was greater than previously believed if the angle of incidence of the shock wave was between 90° and some limiting angle. As a result, it was determined that the effectiveness of an atomic bomb would be enhanced with detonation some kilometers above the target, rather than at ground level.[15]

Beginning in the spring of 1945, along with four other scientists and various military personnel, von Neumann was included in the target selection committee responsible for choosing the Japanese cities of Hiroshima and Nagasaki as the first targets of the atomic bomb. Von Neumann oversaw computations related to the expected size of the bomb blasts, estimated death tolls, and the distance above the ground at which the bombs should be detonated for optimum shock wave propagation and thus maximum effect.[16] The cultural capital Kyoto, which had been spared the firebombing inflicted upon militarily significant target cities like Tokyo in World War II, was von Neumann's first choice, a selection seconded by Manhattan Project leader General Leslie Groves. However, this target was dismissed by Secretary of War Henry Stimson.[17]

On July 16, 1945, with numerous other Los Alamos personnel, von Neumann was an eyewitness to the first atomic bomb blast, conducted as a test of the implosion method device, 35 miles (56 km) southeast of Socorro, New Mexico. Based on his observation alone, von Neumann estimated the test had resulted in a blast equivalent to 5 kilotons of TNT, but Enrico Fermi produced a more accurate estimate of 10 kilotons by dropping scraps of torn-up paper as the shock wave passed his location and watching how far they scattered. The actual power of the explosion had been between 20 and 22 kilotons.[15]

After the war, Robert Oppenheimer remarked that the physicists involved in the Manhattan project had "known sin". Von Neumann's response was that "sometimes someone confesses a sin in order to take credit for it."

Von Neumann continued unperturbed in his work and became, along with Edward Teller, one of those who sustained the hydrogen bomb project. He then collaborated with Klaus Fuchs on further development of the bomb, and in 1946 the two filed a secret patent on "Improvement in Methods and Means for Utilizing Nuclear Energy", which outlined a scheme for using a fission bomb to compress fusion fuel to initiate a thermonuclear reaction. (Herken, pp. 171, 374). Though this was not the key to the hydrogen bomb — the Teller-Ulam design — it was judged to be a move in the right direction.

Computer science

Von Neumann's hydrogen bomb work was also played out in the realm of computing, where he and Stanislaw Ulam developed simulations on von Neumann's digital computers for the hydrodynamic computations. During this time he contributed to the development of the Monte Carlo method, which allowed complicated problems to be approximated using random numbers. Because using lists of "truly" random numbers was extremely slow for the ENIAC, von Neumann developed a form of making pseudorandom numbers, using the middle-square method. Though this method has been criticized as crude, von Neumann was aware of this: he justified it as being faster than any other method at his disposal, and also noted that when it went awry it did so obviously, unlike methods which could be subtly incorrect.

While consulting for the Moore School of Electrical Engineering at the University of Pennsylvania on the EDVAC project, von Neumann wrote an incomplete set of notes titled the *First Draft of a Report on the EDVAC*. The paper, which was widely distributed, described a computer architecture in which the data and the program are both stored in the computer's memory in the same address space. This architecture became the de facto standard until technology enabled more advanced architectures. The earliest computers were 'programmed' by altering the electronic circuitry. Although the single-memory, stored program architecture became commonly known by the name von Neumann architecture as a result of von Neumann's paper, the architecture's description was based on the work of J. Presper Eckert and John William Mauchly, inventors of the ENIAC at the University of Pennsylvania.[18]

Von Neumann also created the field of cellular automata without the aid of computers, constructing the first self-replicating automata with pencil and graph paper. The concept of a universal constructor was fleshed out in his posthumous work *Theory of Self Reproducing Automata*.[19] Von Neumann proved that the most effective way of performing large-scale mining operations such as mining an entire moon or asteroid belt would be by using self-replicating machines, taking advantage of their exponential growth.

He is credited with at least one contribution to the study of algorithms. Donald Knuth cites von Neumann as the inventor, in 1945, of the merge sort algorithm, in which the first and second halves of an array are each sorted recursively and then merged together.[20] His algorithm for simulating a fair coin with a biased coin[21] is used in the "software whitening" stage of some hardware random number generators.

He also engaged in exploration of problems in numerical hydrodynamics. With R. D. Richtmyer he developed an algorithm defining *artificial viscosity* that improved the understanding of shock waves. It is possible that we would not understand much of astrophysics, and might not have highly developed jet and rocket engines without that work. The problem was that when computers solve hydrodynamic or aerodynamic problems, they try to put too many computational grid points at regions of sharp discontinuity (shock waves). The *artificial viscosity* was a mathematical trick to slightly smooth the shock transition without sacrificing basic physics.

Politics and social affairs

Von Neumann obtained at the age of 29 one of the first five professorships at the new Institute for Advanced Study in Princeton, New Jersey (another had gone to Albert Einstein). He was a frequent consultant for the Central Intelligence Agency, the United States Army, the RAND Corporation, Standard Oil, IBM, and others.

Throughout his life von Neumann had a respect and admiration for business and government leaders; something which was often at variance with the inclinations of his scientific colleagues. He enjoyed associating with persons in positions of power, and this led him into government service.[22]

As President of the Von Neumann Committee for Missiles, and later as a member of the United States Atomic Energy Commission, from 1953 until his death in 1957, he was influential in setting U.S. scientific and military policy. Through his committee, he developed various scenarios of nuclear proliferation, the development of intercontinental and submarine missiles with atomic warheads, and the controversial strategic equilibrium called mutual assured destruction. During a Senate committee hearing he described his political ideology as "violently

anti-communist, and much more militaristic than the norm".

Von Neumann's interest in meteorological prediction led him to propose manipulating the environment by spreading colorants on the polar ice caps in order to enhance absorption of solar radiation (by reducing the albedo), thereby raising global temperatures. He also favored a preemptive nuclear attack on the USSR, believing that doing so could prevent it from obtaining the atomic bomb.[23]

Personality

Von Neumann invariably wore a conservative grey flannel business suit - he was even known to play tennis wearing his business suit - and he enjoyed throwing large parties at his home in Princeton, occasionally twice a week.[24] His white clapboard house at 26 Westcott Road was one of the largest in Princeton. [25] Despite being a notoriously bad driver, he nonetheless enjoyed driving (frequently while reading a book) - occasioning numerous arrests as well as accidents. He reported one of his car accidents in this way: "I was proceeding down the road. The trees on the right were passing me in orderly fashion at 60 miles per hour. Suddenly one of them stepped in my path."[26] (The von Neumanns would return to Princeton at the beginning of each academic year with a new car.) It was said of him at Princeton that, while he was indeed a demigod, he had made a detailed study of humans and could imitate them perfectly.[27]

Von Neumann liked to eat and drink heavily; his wife, Klara, said that he could count everything except calories. He enjoyed Yiddish and "off-color" humor (especially limericks).[12]

Honors

The John von Neumann Theory Prize of the Institute for Operations Research and the Management Sciences (INFORMS, previously TIMS-ORSA) is awarded annually to an individual (or group) who have made fundamental and sustained contributions to theory in operations research and the management sciences.

The IEEE John von Neumann Medal is awarded annually by the IEEE "for outstanding achievements in computer-related science and technology."

The John von Neumann Lecture is given annually at the Society for Industrial and Applied Mathematics (SIAM) by a researcher who has contributed to applied mathematics, and the chosen lecturer is also awarded a monetary prize.

The crater Von Neumann on the Moon is named after him.

The John von Neumann Computing Center in Princeton, New Jersey (40°20′55″N 74°35′32″W) was named in his honour.

The professional society of Hungarian computer scientists, John von Neumann Computer Society, is named after John von Neumann.[28]

On February 15, 1956, Neumann was presented with the Presidential Medal of Freedom by President Dwight Eisenhower.

On May 4, 2005 the United States Postal Service issued the *American Scientists* commemorative postage stamp series, a set of four 37-cent self-adhesive stamps in several configurations. The scientists depicted were John von Neumann, Barbara McClintock, Josiah Willard Gibbs, and Richard Feynman.

The John von Neumann Award of The Rajk László College for Advanced Studies was named in his honour, and has been given every year since 1995 to professors who have made an outstanding contribution to the exact social sciences and through their work have strongly influenced the professional development and thinking of the members of the college.

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See also

- Stone–von Neumann theorem
- Von Neumann–Bernays–Gödel set theory
- Von Neumann algebra
- Von Neumann architecture
- Von Neumann bicommutant theorem
- Von Neumann conjecture
- Von Neumann entropy
- Von Neumann programming languages
- Von Neumann regular ring
- Von Neumann universal constructor
- Von Neumann universe
- Self-replicating spacecraft

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- Oral history interview with Eugene P. Wigner [37], Charles Babbage Institute, University of Minnesota, Minneapolis. Wigner talks about his association with John von Neumann during their school years in Hungary, their graduate studies in Berlin, and their appointments to Princeton in 1930. Wigner discusses von Neumann's contributions to the theory of quantum mechanics, and von Neumann's interest in the application of theory to the atomic bomb project.
- Oral history interview with Nicholas C. Metropolis [38], Charles Babbage Institute, University of Minnesota. Metropolis, the first director of computing services at Los Alamos National Laboratory, discusses John von Neumann's work in computing. Most of the interview concerns activity at Los Alamos: how von Neumann came to consult at the laboratory; his scientific contacts there, including Metropolis; von Neumann's first hands-on

experience with punched card equipment; his contributions to shock-fitting and the implosion problem; interactions between, and comparisons of von Neumann and Enrico Fermi; and the development of Monte Carlo techniques. Other topics include: the relationship between Alan Turing and von Neumann; work on numerical methods for non-linear problems; and the ENIAC calculations done for Los Alamos.

- Von Neumann vs. Dirac [39] — from *Stanford Encyclopedia of Philosophy.*
- Edward Teller talking about von Neumann [40] on Peoples Archive.
- A Discussion of Artificial Viscosity [41]
- John von Neumann Postdoctoral Fellowship - Sandia National Laboratories [42]
- Von Neumann's Universe [43], audio talk by George Dyson
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- John von Neumann [45] at the Mathematics Genealogy Project
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[10] While there is a general agreement that the initially discovered bone tumor was a secondary growth, sources differ as to the location of the primary cancer. While Macrae gives it as pancreatic, the *Life* magazine article says it was prostate.

[11] The question of whether or not von Neumann had formally converted to Catholicism upon his marriage to Mariette Kövesi (who was Catholic) is addressed by Halmos (ref. 5). He was baptised Roman Catholic but he certainly was not a practicing member of that religion after his divorce.

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[22] see MAA documentary, especially comments by Morgenstern regarding this aspect of von Neumann's personality

[23] See, *e.g.*, Macrae page 332 and Heims, pages 236 - 247.

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Ilya Prigogine

Ilya Prigogine	
Born	25 January 1917 Moscow, Russia
Died	28 May 2003 (aged 86) Brussels, Belgium
Nationality	Belgium
Fields	Chemistry, Physics
Institutions	Université Libre de Bruxelles International Solvay Institute University of Texas, Austin
Alma mater	Université Libre de Bruxelles
Doctoral advisor	Théophile de Donder
Doctoral students	Adi Bulsara Radu Balescu
Known for	Dissipative structures
Notable awards	Nobel Prize for Chemistry (1977)

Ilya, Viscount Prigogine (Russian: Илья́ Рома́нович Приго́жин) (25 January 1917 – 28 May 2003) was a Russian-born naturalized Belgian physical chemist and Nobel Laureate noted for his work on dissipative structures, complex systems, and irreversibility.

Biography

Prigogine was born in Moscow a few months before the Russian Revolution of 1917. His father, Roman (Ruvim Abramovich) Prigogine, was a chemical engineer at the Moscow Institute of Technology; his mother, Yulia Vikhman, was a pianist. Because the family was critical toward the new Soviet system, they left Russia in 1921. They first went to Germany and in 1929 to Belgium, where Prigogine received Belgian citizenship in 1949.

Prigogine studied chemistry at the Free University of Brussels, where in 1950 he became professor. In 1959, he was appointed director of the International Solvay Institute in Brussels, Belgium. In that year he also started teaching at the University of Texas at Austin in the United States, where he later was appointed Regental Professor and Ashbel Smith Professor of Physics and Chemical Engineering. From 1961 until 1966 he was affiliated with the Enrico Fermi Institute at the University of Chicago. In Austin, in 1967, he co-founded what is now called The Center for Complex Quantum Systems. In that year he also returned to Belgium where he became director of the *Center for Statistical Mechanics and Thermodynamics*.

He was a member of numerous scientific organizations, and received numerous awards, prizes and 53 honorary degrees. In 1955 Ilya Prigogine was awarded the Francqui Prize for Exact Sciences. For this study in irreversible thermodynamics he received the Rumford Medal in 1976 and in 1977 the Nobel Prize in Chemistry. In 1989 he was awarded the title of Viscount by the King of Belgium. Until his death he was president of the International Academy of Science and was in 1997 one of the founders of the International Commission on Distance Education (CODE), a worldwide accreditation agency.

Prigogine was married to Polish-born chemist Maryna Prokopowicz(-Prigogine) in 1961. They have two sons.

Research

Prigogine is known best due to his definition of dissipative structures and their role in thermodynamic systems far from equilibrium, a discovery that won him the Nobel Prize in Chemistry in 1977.

Dissipative structures theory

Dissipative structure theory led to pioneering research in self-organizing systems, as well as philosophic inquiries into the formation of complexity on biological entities and the quest for a creative and irreversible role of time in the natural sciences.

His work is seen by many as a bridge between natural sciences and social sciences. With professor Robert Herman he also developed the basis of the two fluid model, a traffic model in traffic engineering for urban networks, in parallel to the two fluid model in Classical Statistical Mechanics.

Other work

In his later years, his work concentrated on the mathematical role of determinism in nonlinear systems on both the classical and quantum level. He proposed the use of a rigged Hilbert space in quantum mechanics as one possible method of achieving irreversibility in quantum systems. He also co-authored several books with Isabelle Stengers, including *End of Certainty* and the classical book *La Nouvelle Alliance* (*The New Alliance*).

The End of Certainty

In his 1997 book, *The End of Certainty*, Prigogine contends that determinism is no longer a viable scientific belief. "The more we know about our universe, the more difficult it becomes to believe in determinism." This is a major departure from the approach of Newton, Einstein and Schrödinger, all of whom expressed their theories in terms of deterministic equations. According to Prigogine, determinism loses its explanatory power in the face of irreversibility and instability.

Prigogine traces the dispute over determinism back to Darwin, whose attempt to explain individual variability according to evolving populations inspired Ludwig Boltzmann to explain the behavior of gases in terms of populations of particles rather than individual particles. This led to the field of statistical mechanics and the realization that gases undergo irreversible processes. In deterministic physics, all processes are time-reversible, meaning that they can proceed backward as well as forward through time. As Prigogine explains, determinism is fundamentally a denial of the arrow of time. With no arrow of time, there is no longer a privileged moment known as the "present," which follows a determined "past" and precedes an undetermined "future." All of time is simply given, with the future as determined or undetermined as the past. With irreversibility, the arrow of time is reintroduced to physics. Prigogine notes numerous examples of irreversibility, including diffusion, radioactive decay, solar radiation, weather and the emergence and evolution of life. Like weather systems, organisms are unstable systems existing far from thermodynamic equilibrium. Instability resists standard deterministic explanation. Instead, due to sensitivity to initial conditions, unstable systems can only be explained statistically, that is, in terms of probability.

Prigogine asserts that Newtonian physics has now been "extended" three times, first with the use of the wave function in quantum mechanics, then with the introduction of spacetime in general relativity and finally with the recognition of indeterminism in the study of unstable systems.

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See also

- Autocatalytic reactions and order creation

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Gregory Bateson

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Born	9 May 1904 Grantchester, UK
Died	July 4, 1980 (aged 76) San Francisco, USA
Fields	anthropology, social sciences, linguistics, cybernetics, systems theory
Known for	Double Bind, Ecology of mind, deuterolearning, Schismogenesis
Influenced	Application of type theory in social sciences, Richard Bandler, Brief therapy, Communication theory, Gilles Deleuze, Ethnicity theory[1] , Evolutionary biology, Family therapy, John Grinder, Félix Guattari, Jay Haley, Don D. Jackson, Bradford Keeney, Stephen Nachmanovitch, Neuro-linguistic programming, Systemic coaching, William Irwin Thompson, Visual anthropology, Paul Watzlawick

Gregory Bateson (9 May 1904 – 4 July 1980) was a British anthropologist, social scientist, linguist, visual anthropologist, semiotician and cyberneticist whose work intersected that of many other fields. Some of his most noted writings are to be found in his books, *Steps to an Ecology of Mind* (1972) and *Mind and Nature* (1979). *Angels Fear* (published posthumously in 1987) was co-authored by his daughter Mary Catherine Bateson.

Biography

Bateson was born in Grantchester, UK on 9 May 1904, the youngest of three sons of distinguished geneticist William Bateson and his wife, [Caroline] Beatrice Durham. He attended Charterhouse School from 1917 to 1921. He obtained a BA in biology at St. John's College, Cambridge in 1925 and continued at Cambridge from 1927 to 1929. Bateson lectured in linguistics at the University of Sydney 1928. From 1931 to 1937 he was a Fellow of St. John's College, Cambridge[2] and then moved to the United States.

In Palo Alto, Gregory Bateson and his colleagues Donald Jackson, Jay Haley and John H. Weakland developed the double bind theory *(see also Bateson Project)*.[3]

One of the threads that connects Bateson's work is an interest in systems theory and cybernetics, a science he helped to create as one of the original members of the core group of the Macy Conferences. Bateson's take on these fields centres upon their relationship to epistemology, and this central interest provides the undercurrents of his thought. His association with the editor and author Stewart Brand was part of a process by which Bateson’s influence widened — for from the 1970s until Bateson’s last years, a broader audience of university students and educated people working in many fields came not only to know his name but also into contact to varying degrees with his thought.

In 1956, he became a naturalized citizen of the United States. Bateson was a member of William Irwin Thompson's Lindisfarne Association. In the 1970s, he taught at the Humanistic Psychology Institute in San Francisco--which is now Saybrook University[4]--and also served as a lecturer and fellow of Kresge College at the University of California, Santa Cruz. In 1978, California Governor Jerry Brown appointed Bateson to the Board of Regents of the University of California, in which position he served until his death.

Personal life

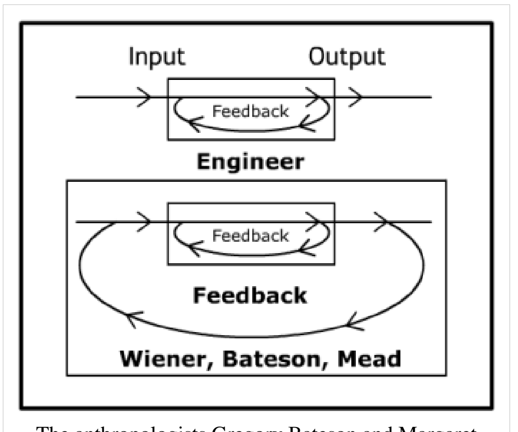
Bateson's life was greatly affected by the death of his two brothers. John Bateson (1898-1918), the eldest of the three, was killed in World War I. Martin Bateson (1900-1922), the second brother, was then expected to follow in his father's footsteps as a scientist, but came into conflict with William over his ambition to become a poet and playwright. The resulting stress, combined with a disappointment in love, resulted in Martin's public suicide by gunshot under the statue of Anteros in Piccadilly Circus, on 22 April 1922, which was John's birthday. After this event, which transformed a private family tragedy into public scandal, all William and Beatrice's ambitious expectations fell on Gregory Bateson, their only surviving son.[5]

Bateson's first marriage, in 1936, was to American cultural anthropologist Margaret Mead.[6] Bateson and Mead had a daughter, Mary Catherine Bateson (born 1939), who also became an anthropologist.

Bateson decided to separate from Mead in 1947, and they were formally divorced in 1950.[7] Bateson then married his second wife, Elizabeth "Betty" Sumner (1919-1992), in 1951.[8] She was the daughter of the Episcopalian Bishop of Chicago, Walter Taylor Sumner. They had a son, John Sumner Bateson (born 1952), as well as twins who died in infancy. Bateson and Sumner were divorced in 1957, after which Bateson married his third wife, therapist and social worker Lois Cammack (born 1928), in 1961. They had one daughter, Nora Bateson (born 1969).[9] Nora is married to drummer Dan Brubeck, son of jazz musician Dave Brubeck.

Work

Double bind



The anthropologists Gregory Bateson and Margaret Mead contrasted first and Second-order cybernetics with this diagram in an interview in 1973.[10]

In 1956 in Palo Alto Gregory Bateson and his colleagues Donald Jackson, Jay Haley, and John Weakland [3] articulated a related theory of schizophrenia as stemming from double bind situations. The perceived symptoms of schizophrenia were therefore an expression of this distress, and should be valued as a cathartic and transformative experience. The double bind refers to a communication paradox described first in families with a schizophrenic member.

Full double bind requires several conditions to be met:

1. The victim of double bind receives contradictory injunctions or emotional messages on different levels of communication (for example, love is expressed by words, and hate or detachment by nonverbal behaviour; or a child is encouraged to speak freely, but criticised or silenced whenever he or she actually does so).
2. No metacommunication is possible – for example, asking which of the two messages is valid or describing the communication as making no sense.
3. The victim cannot leave the communication field.
4. Failing to fulfill the contradictory injunctions is punished (for example, by withdrawal of love).

The double bind was originally presented (probably mainly under the influence of Bateson's psychiatric co-workers) as an explanation of part of the etiology of schizophrenia. Currently, it is considered to be more important as an example of Bateson's approach to the complexities of communication.

Other terms used by Bateson

- **Abduction**. Used by Bateson to refer to a third scientific methodology (along with induction and deduction) which was central to his own holistic and qualitative approach. Refers to a method of comparing patterns of relationship, and their symmetry or asymmetry (as in, for example, comparative anatomy), especially in complex organic (or mental) systems. The term was originally coined by American Philosopher/Logician Charles Sanders Peirce, who used it to refer to the process by which scientific hypotheses are generated.
- **Criteria of Mind (from *Mind and Nature A Necessary Unity*)**:[11]

1. Mind is an aggregate of interacting parts or components.
2. The interaction between parts of mind is triggered by difference.
3. Mental process requires collateral energy.
4. Mental process requires circular (or more complex) chains of determination.
5. In mental process the effects of difference are to be regarded as transforms (that is, coded versions) of the difference which preceded them.
6. The description and classification of these processes of transformation discloses a hierarchy of logical types immanent in the phenomena.

- **Creatura and Pleroma**. Borrowed from Carl Jung who applied these gnostic terms in his "Seven Sermons To the Dead".[12] Like the Hindu term maya, the basic idea captured in this distinction is that meaning and organization are projected onto the world. Pleroma refers to the non-living world that is undifferentiated by subjectivity; Creatura for the living world, subject to perceptual difference, distinction, and information.
- **Deuterolearning**. A term he coined in the 1940s referring to the organization of learning, or learning to learn:[13]
- **Schismogenesis** - the emergence of divisions within social groups.
- Bateson defines information as "a difference which makes a difference." For Bateson, information in fact mediated Alfred Korzybski's map–territory relation, and thereby resolved the mind-body problem. [14] [15]

See also

- Complex systems
- Constructivist epistemology
- Cybernetics
- Family therapy
- Holism
- Mind-body problem
- Second-order cybernetics
- Systems theory in anthropology
- Systems thinking
- Systems philosophy

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- 1978, Malcolm, J., "The One-Way Mirror" (reprinted in the collection "The Purloined Clinic"). Ostensibly about family therapist Salvador Minuchin, essay digresses for several pages into a meditation on Bateson's role in the origin of family therapy, his intellectual pedigree, and the impasse he reached with Jay Haley.

Documentary film

- *Trance and Dance in Bali*, a short documentary film shot by cultural anthropologist Margaret Mead and Gregory Bateson in the 1930s, but it was not released until 1952. In 1999 the film was deemed "culturally significant" by the United States Library of Congress and selected for preservation in the National Film Registry.

Trivia

- Bateson is often given as the origin of the story concerning the replacement of the huge oak beams of the main hall of New College, Oxford with trees planted on college land several hundred years previously for that express purpose[16] . Although the precise facts do not entirely match the story, it is commonly cited as an admirable example of planning ahead.[17]

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- 1992 Gregory Bateson's Theory of Mind : Practical Applications to Pedagogy [19] by Lawrence Bale. Nov. 1992, (Published online by Lawren Bale, D&O Press, Nov. 2000).
- Article *The Double Bind: The Intimate Tie Between Behaviour and Communication* [20] by Patrice Guillaume
- 1995, Paper *Gregory Bateson: Cybernetics and the social behavioral sciences* [21] by Lawrence S. Bale, Ph.D.: First Published in: *Cybernetics & Human Knowing: A Journal of Second Order Cybernetics & Cyber-Semiotics*, Vol. 3 no. 1 (1995), pp. 27–45.
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- 2005, "Gregory Bateson and Ecological Aesthetics" [25] Peter Harries-Jones, in: *Australian Humanities Review* (Issue 35, June 2005)
- 2005, "Chasing Whales with Bateson and Daniel" [26] by Katja Neves-Graça,
- 2005, "Pattern, Connection, Desire: In honour of Gregory Bateson" [27] by Deborah Bird Rose.
- 2005, "Comments on Deborah Rose and Katja Neves-Graca" [28] by Mary Catherine Bateson
- 2008. "A Legacy for Living Systems: Gregory Bateson as Precursor to Biosemiotics A Legacy for Living Systems: Gregory Bateson as Precursor to Biosemiotics", by Jesper Hoffmeyer (ed.)

External links

- Book "A Recursive Vision: Ecological Understanding and Gregory Bateson" [29] by Peter Harries-Jones
- Book "Understanding Gregory Bateson" [30] by Noel Charlton
- "Institute for Intercultural Studies" [31]
- "Six days of dying" [32]; essay by Catherine Bateson describing Gregory Bateson's death
- "Bateson's Influence on Family Therapy" [33] ; inside details by MindForTherapy

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Otto Rössler

Otto E. Rössler (born 20 May 1940) is a German biochemist.

Biography

Rössler was born in Berlin. At the age of 17, he became an amateur radio operator (DR 9KF). After considering becoming a monk, Rössler chose to major in medicine, with a speciality in immunology, for ethical reasons.

He was awarded his MD in 1966. Rössler then began his post doc at the Max Planck Institute for Behavioral Psychology, in Bavaria. In 1969, he started a visiting appointment at the Center for Theoretical Biology at SUNY-Buffalo. Later that year, he became Professor for Theoretical Biochemistry at the University of Tübingen. In 1976, he became a tenured University Docent. In 1994, he became Professor of Chemistry by decree.

Rössler has held visiting positions at the University of Guelph (Mathematics) in Canada, the Center for Nonlinear Studies [1] of the University of California at Los Alamos, the University of Virginia (Chemical Engineering), the Technical University of Denmark (Theoretical Physics), and the Santa Fe Institute (Complexity Research) in New Mexico.

In June 2008 Rössler emerged in the public eye with an open letter[2] as one of the strongest critics of the Large Hadron Collider (LHC) proton collision experiment supervised by the European Organization for Nuclear Research in Geneva, trying to raise awareness of the possibility of creating human-made uncontrollable mini black holes with assumed exponential growth which might get trapped in Earth's gravity due to their slowness of movement compared to the natural phenomenon of proton collisions with cosmic rays.

He based his warnings on a known but hardly noticed proposition made by Max Abraham in 1912 surrounding Albert Einstein's theory of relativity as well as his own, yet theoretically disputed [3] [4] [5] , *gothic* - $\mathfrak{R}$ theorem and its implications.[6] He also questioned the existence of the Hawking radiation which in theory should lead to the decay of micro black holes. A majority of experts in these fields dismissed his claims as substantial misconceptions of the general theory of relativity, as well as being inconsistent and disproved through measurement experiments. [7] [8] [9] [10]

Apart from the refutation of his theory, which he challenged others to debate, his public step up and call for an LHC Safety Conference[11] started a discussion about the ethical limits of modern experimental physics in mainstream media all across Europe.

Rössler has authored around 300 scientific papers in fields as wide-ranging as biogenesis, the origin of language, differentiable automata, chaotic attractors, endophysics, micro relativity, artificial universes, the hypertext encyclopedia, and world-changing technology.

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See also

- Rössler attractor

External links

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- Otto Rössler [14]: From the origin of life to the architecture of chaos. (20 October 2004). *Analyse Topologique et Modélisation de Systèmes Dynamiques.*

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